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New energy analysis process for the design of building retrofits

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Aalto University
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Tiivistelmä

Rakennusten energia-analyysien ja simulointien merkitys on kasvanut merkittävästi viime vuosien aikana johtuen yhä monimutkaisemmista rakennuksista ja vaativammista rakentamismääräyksistä. Myös energiatehokas korjausrakentaminen on ajankohtainen tutkimusaihe, koska nykyisessä rakennuskannassa on huomattavaa säästöpotentiaalia sekä energiassa että kustannuksissa. Nykyinen rakennusten suunnittelukulttuuri ei kuitenkaan hyödynnä energia-analyysien täyttä potentiaalia. Tässä työssä kehitettiin ja testattiin uutta energia-analyysiprosessia rakennusten korjaushankkeisiin. Uuden prosessin tarkoitus on tukea korjaushankkeiden suunnittelua ja interaktiivista päätöksentekoa nykyistä tehokkaammin, sekä ohjata korjaushankkeisiin liittyvää tiedonkeruuta.

Kehitetty prosessi hyödyntää useita menetelmiä, mukaan lukien rakennusten tietomallinnuksen, dynaamiset energiasimuloinnit, sekä herkkyys- ja epävarmuusanalyysit. Tietomallinnuksen käyttö mahdollistaa helpomman tiedon varastoinnin ja saatavuuden koko prosessin aikana ja mahdollistaa tarkkojen dynaamisten energiasimulointi-ohjelmien käytön. Herkkyysanalyysiä käytetään tiedonkeruun tukemiseen sekä apuna optimaalisen suunnitteluratkaisun löytämiseen. Epävarmuusanalyysin avulla pystytään tekemään paremmin perusteltuja päätöksiä. Prosessi on jaettu kahteen erilliseen vaiheeseen, joille on asetettu erilaiset vaatimukset lähtötietojen ja tietomallin tarkkuudelle. Molemmissa vaiheissa suoritetaan suuri määrä parametrisoituja simulointeja, mikä mahdollistaa herkkyys- ja epävarmuusanalyysien käytön. Kehitetty prosessi pohjautuu osittain aikaisempaan tutkimukseen. Tässä työssä on määritelty prosessin kulku, sekä uusina elementteinä lisätty epävarmuusanalyysin hyödyntäminen ja herkkyysanalyysin tulosten painotettu visualisointi.

Työ sisälsi myös kehitetyn prosessin ja sen ominaisuuksien testaamisen pilottikohteessa, minkä perusteella prosessin toimivuutta arvioitiin. Pilotoinnissa käytettiin RIUSKA-ohjelmistoa, koska sillä pystytään helposti simuloimaan suuria määriä parametrisoituja energiasimulointeja. Pilotoinnista saadut tulokset osoittivat, että kehitetyn prosessin avulla energiasimulointien tuloksia voidaan tehokkaasti hyödyntää suunnittelun ja päätöksenteon tukena jo projektin ensimmäisistä vaiheista lähtien. Epävarmuus-analyysillä oli merkittävä vaikutus lopullisen suunnitteluratkaisun valinnassa, ja se todettiin tärkeäksi osaksi prosessia. Vaikka prosessi vaatii vielä jatkokehitystä ja laajempaa pilotointia, voisi tämän kaltaisen energia-analyysiprosessin sisällyttäminen korjaushankkeiden suunnitteluun olla tärkeä askel kohti tehokkaampaa tapaa hyödyntää energiasimulointeja.

Avainsanat Energia-analyysi, energiasimulointi, rakennusten tietomallinnus, herkkyysanalyysi, epävarmuusanalyysi, visualisointi, parametrisointi

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Abstract

Building energy simulation and analysis have gained considerable attention in recent years, due to increasingly complex building design and ever more demanding building regulations. In addition, extensive efforts have focused on energy efficient retrofitting of existing buildings, because of the high energy- and cost-saving potential of the existing building stock. However, the current building design culture has not yet utilized the full potential of energy analysis. Although many advanced methods already exist for supporting energy analysis, no clear process has yet been established for efficiently using these methods in existing building stock. Therefore, this thesis developed and tested a new process for energy analysis in neighborhood-scale retrofit projects. The proposed process aims to support interactive multi-criteria decision making and to guide designers in the challenging data collection task faced during retrofit projects.

The new process utilizes several advanced methods, namely building information modeling (BIM), dynamic energy simulations, as well as sensitivity and uncertainty analyses. Utilizing BIM allows easier storage and retrieval of information throughout the process and allows the usage of more accurate dynamic energy simulation software. The sensitivity analysis is used to support the data collection task and to guide the search for the optimal retrofit solution. The uncertainty analysis enables more justified decisions to be made. The process is divided into two operational modes, the basic and the advanced modes, with different requirements for their input data. A large number of parametrized simulations is performed in both modes, as required by the sensitivity and uncertainty analyses. The developed process is partly based on previous work, which was continued in this thesis by determining the process flow in both operational modes, as well as by including the uncertainty analysis and the weighted visualization method for sensitivity analysis in the process.

The process was tested using a real pilot neighborhood, which made it possible to evaluate the functionality of the process. The energy and comfort simulation software RIUSKA was used in the piloting, because of its automated feature for parametrized simulation. The results demonstrated that the new process shows promise, although it still requires further testing and development. The uncertainty analysis was found to be an important part of the process. Implementing such an energy analysis process in the design of building retrofits could offer an important step towards a more efficient approach for utilizing energy simulations. Using this process could enable energy simulations to be used for guiding the design process already in the first phases of the project in order to effectively support decision making throughout the entire project.

Keywords Energy analysis, energy simulation, building information modeling, sensitivity analysis, uncertainty analysis, retrofit design, visualization, parametrization

Preface

This thesis has been written for Granlund Oy as a part of its research and development activity. The work was financed by Granlund and the NewTREND EU Project. This thesis was supervised by Professor Risto Kosonen from Aalto University. The advisor for this thesis was Tuomas Laine, director of Granlund's innovation and development department.

I would like to thank Granlund Oy and the NewTREND project for the financing of this thesis and making it possible to write my thesis on this interesting topic. I would like to express my gratitude to Risto Kosonen for his flexible guidance and valuable comments. I would also like to thank Tuomas Laine for his essential guidance and support, which was especially important at the beginning of this work.

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Espoo 04.10.2016

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Contents

Abbreviations

AHU	Air Handling Unit
AIA	American Institute of Architects
BES	Building Energy Simulation
BIM	Building Information Modeling
CAD	Computer-Aided Design
COBIM	Common Building Information Modeling Requirements
CSV	Comma-separated Values
DCV	Demand Controlled Ventilation
DHW	Domestic Hot Water
ECDF	Empirical Cumulative Distribution Function
FM	Facility Management
HRU	Heat Recovery Unit
HVAC	Heating Ventilation and Air Conditioning
IC	Influence Coefficient
IFC	Industry Foundation Classes
IQR	Interquartile Range
KPA	Key Point Analysis
KPI	Key Performance Indicator
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LOD	Level of Detail or Level of Development
MEP	Mechanical, Electrical, and Plumbing services
NPV	Net Present Value
O&M	Operations and Maintenance
PCC	Partial Correlation Coefficient
PCP	Parallel Coordinate Plot
PDF	Probability Density Function
PRCC	Partial Rank Correlation Coefficient
SA	Sensitivity Analysis
SFP	Specific Fan Power
SRC	Standardized Regression Coefficient
SRRC	Standardized Rank Regression Coefficient
UA	Uncertainty Analysis
VAV	Variable Air Volume
XML	Extensive Markup Language
IES VE	Integrated Environmental Solutions Virtual Environment

1 Introduction

1.1 Background

In recent years, it has become increasingly evident that the existing building stock in Europe consumes an excessive amount of energy, thus making the energy efficient retrofitting of buildings an important research topic. In fact, the existing building stock is responsible for 40% of total energy consumption as well as 36% of total CO_2 emissions in the European Union [1]. Moreover, it has been estimated that the buildings that exist today will account for approximately 70% of Europe's building stock by 2050 [2]. Old buildings tend to consume significantly more energy than those recently built. These issues have led the EU to set two directives, the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive, for reducing the energy consumption of new and existing buildings, respectively [1]. One result of these directives is that they have compelled EU countries to set their own national energy performance requirements for both new buildings and the retrofitting of existing buildings.

In Finland, the Ministry of Environment [3] set new energy regulations for constructing new buildings in 2012. These new regulations encourage the use of renewables and comprehensive management of energy consumption, as well as tighten the required energy efficiency requirements by approximately 20%. Furthermore, the most substantial development was that Finnish building regulations now require that the total energy consumption be calculated using specified weighting factors for different energy carriers. For example, electricity has a weighing factor of 1,7 and district heating a factor of 0,7. All individual sources of energy consumption used in a building are added together, also including the energy use for ventilation, hot water and lighting. In Finland, the total energy consumption calculated in this manner is referred to as the "E-value", which is used as a basis for obligatory energy certificates. The use of the E-value increases the flexibility of building design, as the energy requirements can be achieved in numerous different ways. [3] In 2013, regulations for energy efficient renovation of existing buildings were also set in Finland [4]. These regulations stipulate that designers use one of three approaches to reduce energy consumption: (1) improve the thermal properties of the building elements to meet specified requirements; (2) lower the standard energy consumption per surface area to the level defined for each building type; or (3) decrease the E-value to a building-specific level. Furthermore, if technical systems, such as heating and ventilation systems, are being retrofitted, they need to meet certain requirements. [4] Again, these options offer designers the flexibility needed for case-specific retrofit projects.

The high energy-saving potential of buildings has also stimulated the development of many advanced technologies for reducing the energy demand of buildings, including improved insulation materials, efficient heat recovery systems and renewable energy generation [5]. However, despite the availability of needed technologies and the directives set by the European Union, the average renovation rate in the EU still remains at only about 1% per year [6]. This modest renovation rate could be explained by the many problems faced in these projects. Naaranoja and Uden [7] analyzed the problems faced in renovation projects in Finland and identified several common problems, including the lack of decision-making process, the lack of risk assessment and failure to learn from successful projects. One significant problem is that the current design and construction process is still rather unstructured, often leading to insufficient collaboration between different actors. Another challenge is that the information about the current condition of the building is often unavailable, outdated, uncertain or dispersed between numerous sources. Moreover, challenges concerning building design, in general, include complexity of modern buildings [8] and inefficient use of energy analysis [9]. Efficiently utilizing advanced methods, such as dynamic energy simulations, building information modeling (BIM), as well as sensitivity and uncertainty analysis, could address these challenges.

Building design is a complicated combination of multiple engineering disciplines: (1) architectural, (2) heating, ventilation and air-conditioning (HVAC), (3) structural, (4) electrical and (5) automation. In building design, it has always been a challenge to achieve high indoor air quality, while maintaining costs at an acceptable level. Now, tight energy targets are added into the mix, making the building design even more demanding. Moreover, the amount of available materials and technical system options is constantly increasing. This is, of course, a favorable development, but it also means that the number of possible design combinations have increased dramatically, causing the decision making process in the building design to become even more challenging. In addition, modern buildings consist of multiple subsystems that have non-trivial effects on other systems, which makes it difficult to estimate the effects of different design solutions on the total building energy performance. [8, 10] This complexity could be overcome by using dynamic simulations to more accurately analyze the energy consumption of buildings.

Energy analysis of buildings is a tool used for analyzing the energy flows in and out of a building. In addition to energy aspects, indoor environment calculations are also often defined to be included in energy analysis, as they are closely linked together. [11] Recently, energy analysis of buildings has gained increased attention due to ever more demanding building regulations. As the design of buildings is becoming increasingly challenging, energy analysis has been established as a crucial tool in guiding the design process towards more energy efficient solutions. [10, 12] Despite the importance of energy analysis, it is still often done using rather inaccurate statistical estimates or static calculations [11, 12]. Another issue concerning current practices in energy analysis is that it is traditionally often used only in the final stages of the project to confirm that the design complies with regulations and to set targets for the energy consumption [9, 13]. Thus, energy analysis has unused potential in supporting the design process during the earlier phases as well.

The use of building information modeling (BIM) has become more commonly used in the design and construction process of new buildings. Simply put, BIM means creating three-dimensional, object-oriented models of the building, with further information added to each of their components. Utilizing BIM has many benefits, including improved visualization, easier collaboration between designers, easier retrieval of information and more effective design process. [14] Also, it allows much easier use of more accurate dynamic energy simulations for energy analysis, as the BIM model can be used as a data source for many energy simulation tools. [12] However, BIM has rarely been implemented in retrofitting projects. The main reason for this is the difficulties in collecting the required data to create a BIM model. [15]

Uncertainties play an important role in analyzing the energy consumption of buildings. Some input parameters of the simulation model, such as weather and operating schedules of air conditioning, often cannot be known accurately beforehand. These uncertainties should be taken into account in order to make justified design decisions. This can be done by utilizing sensitivity and uncertainty analyses. [13] In retrofit projects, the information is often outdated, if found at all. Moreover, time causes the structures of existing buildings to deteriorate, making it challenging to determine the thermal properties of the envelope. [16] Therefore, uncertainties caused by a lack of information have an even greater influence on retrofit projects.

Although these advanced methods (i.e. dynamic simulations, BIM, sensitivity analysis and uncertainty analysis) have already been used in energy analyses to some extent, no clear process has yet been established for efficiently using these methods in existing building stock. Recently, Stjelja [17] introduced a new approach for energy analysis of existing buildings in his master's thesis. His work presented a BIM-based process for energy analysis that could be utilized from the very beginning of a retrofitting project, while taking advantage of sensitivity analysis results. However, this process still requires further development and is in need of piloting on a wider scale. Moreover, it did not include uncertainty analysis, which would be important to make better justified decisions.

1.2 NewTREND project

This thesis forms part of the European Union's NewTREND project, which aims to develop a new software-based methodology to make retrofitting of buildings more efficient and easy. In the long run, the aim of the NewTREND project is to improve the energy efficiency of the existing European building stock and renovation rate. To achieve this goal, an integrated design methodology for building energy retrofit will be developed that addresses all phases of the retrofitting process. The project also aims to encourage collaboration among all stakeholders, involve building inhabitants and establish energy performance as a key component of retrofitting.

1.3 Objectives

<u>The objective of this thesis is to extend and improve the process introduced by Stjelja [17] for energy analysis in neighborhood scale retrofit projects.</u> The process will be used to support interactive multi-criteria decision-making, while taking into account energy efficiency and comfort, as well as environmental and economic aspects. Several advanced methods are utilized in the process, namely BIM, dynamic energy simulations, as well as sensitivity and uncertainty analyses. The process will cover only the pre-construction phases of retrofit projects. The process proposed in this thesis will be used by the engineering office Granlund to develop a new service concept.

In addition to utilizing BIM in dynamic energy simulations, sensitivity and uncertainty analysis also act as essential tools in the process proposed in this thesis. Currently, sensitivity analysis is used mostly in the design phase to help designers identify the most influential inputs. In this work, an approach is described for using sensitivity analysis also in the preliminary stage of retrofit projects to support the challenging task of data collection. The process will be extended to include the use of an uncertainty analysis: methods for analyzing uncertainty and visualizing the results will be investigated. Furthermore, a new weighted visualization method for sensitivity analysis will be developed for the new process. These improved sensitivity and uncertainty analyses will be implemented in the Key Point Analysis tool (KPA) developed by Granlund.

The process and these methods are piloted in a real retrofitting project located in Seinäjoki, Finland. MagiCAD Room is used to create the BIM models because it allows creating an open form IFC-file that supports energy analysis. The NewTREND project will be developed around a simulation software called Integrated Environmental Solutions Virtual Environment (IES VE). However, in terms of sensitivity and uncertainty analysis, the current version of IES VE is not the optimal choice. Both sensitivity and uncertainty analysis require a large number of simulations with varying inputs, which would have to be done manually with IES VE. Therefore, the energy simulation software RIUSKA, which has an automated feature for parametrized simulation, is used in this work instead.

1.4 Structure

The rest of this thesis is organized as follows. Chapter 2 reviews the literature covering the methods used in the process. Chapter 3 describes the development of the process. Chapter 4 presents the piloting of the new process. Chapter 5 discusses the different elements and aspects included in this process, as well as provides further development needs. Finally, Chapter 6 summarizes the work and presents the most important conclusions drawn from the piloting of the process.

2 Advanced methods for energy analysis

In this chapter, advanced methods for energy analysis will be reviewed in the form of a literature survey. The focus will be on how these methods can be used in energy analyses and what is required of each method in the new process.

Section 2.1 briefly presents the common characteristics of building information modeling (BIM), including its utilization in energy analyses and in retrofit projects. Section 2.2 describes the benefits and requirements of dynamic energy simulations, as well as presents the simulation software used in this thesis. Finally, section 2.3 describes the fundamentals of sensitivity and uncertainty analyses, as well as their utilization in building energy analyses.

2.1 Building information modeling

The design of buildings has evolved from using paper and pen to digital computer aided design (CAD) in the 1990s. Currently, another big step is being taken as the construction industry is moving from two-dimensional CAD design to intelligent three-dimensional modeling. Building Information Modeling (BIM) is a term that has been widely established in the industry for this advanced 3D design. [18]

This section briefly describes the common characteristics of BIM, and the important issues related to using it in the new process. First, in Section 2.1.1, definitions and benefits of BIM are presented. Section 2.1.2 presents how BIM can be utilized in energy analyses. Section 2.1.3 discusses the challenges and requirements of utilizing BIM in retrofit projects. Lastly, Section 2.1.4 reviews a few specifications of model accuracy and data richness.

2.1.1 Definition and characteristics

BIM is defined in ISO 29481-1:2010(en) [19] standard as: "*shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions.*" Another definition by the US National Building Information Model Standard Project Committee [20] is that:" *Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition*." More simply put, BIM is creating a 3D geometric model of a building and its components, containing relevant information that is needed in designing, constructing, operating and maintaining the building throughout its lifecycle. In addition to geometric information, objects may have functional, semantic or topologic information [15]. It is important to note that BIM is not just designing in three dimensions, as it also includes information about the building and its components.

In order to give a more precise understanding of what BIM means, the main characteristics of BIM can be described by the following four features [21]:

- Building components are modeled by intelligent objects that recognize what kind of objects they are (e.g. door or window) and can be given data attributes and rules.
- Consistent and non-redundant data, which means that if a change is made in one view, it will also occur in all other views.

- The data included in the building components describe their behavior and can be utilized for analyses and work processes, such as energy simulations.
- The data is coordinated, meaning that all views will be represented in a coordinated way.

The main objective of BIM-based design is to make the whole design and construction process more efficient and easier to control. In addition, it should improve the quality, safety and sustainability of the process. [11, 22] BIM-based design has numerous benefits, including improved visualization and data management, easier coordination between designers, easier retrieval of information and support for different kinds of analyses. In addition, one significant benefit of utilizing BIM is that it allows the design solutions and their functionality to be analyzed throughout the whole lifecycle of the building. BIM can be used in all the disciplines of building design (architectural, structural, HVAC, automation, electricity) to create an integrated model of the building, which makes integrating different disciplines significantly easier. [11, 15, 18] Another important benefit, especially in the framework of this thesis, is that BIM can be used as an information source for many energy simulation tools, thus making the data input faster, easier and less prone to errors [11].

2.1.2 BIM utilization in energy analysis

Energy analysis is an important tool to guide the design process towards energy efficient solutions while maintaining required indoor environment. The energy efficiency and indoor conditions of a building are influenced by architectural, structural and system solutions. Therefore, fluent cooperation between designers throughout the whole project is vital in achieving an optimal total design solution. By utilizing BIM, energy analyses can be more easily done already at the beginning of the project and provide support for collaboration between designers. In addition to estimating energy consumption and indoor conditions, energy analysis can also be used in the HVAC design for the sizing of equipment. [11]

In 2012 was published a series called “Common BIM Requirements 2012” (COBIM), which was funded and written by multiple Finnish companies and organizations. Part 10 of the series [11] covers energy analyses. It describes potential utilization and the requirements of BIM based energy analyses during all construction project stages used in Finland, from conceptual design to operations and maintenance. This section reviews part 10 of COBIM briefly. More detailed information can be found in the paper itself. The potential utilization ways of BIM-based energy analysis are summarized in Figure 2.1 and Figure 2.2 along with required initial data at each stage. This kind of procedure enables beneficial use of energy analyses already in the early design stages by utilizing BIM in multiple ways. [11]

Design and construction projects in Finland are divided into eight phases, all of which can benefit from BIM-based energy analyses (Figure 2.1 and Figure 2.2). First, during the (1) **conceptual design**, energy analysis is used to support set up of energy and comfort requirements. During the (2) **schematic design**, energy analysis is used to compare alternate design solutions and finding the optimal solution. Also, energy and comfort requirements are updated if needed. The use of energy analysis continues in the (3) **design development phase** with further analysis of the selected design solution. In addition, air condition requirements are defined based on the simulations and an estimate is simulated for building’s energy consumption. In Finland, it is necessary to perform an energy survey during the (4) **building permit phase**. A BIM-based energy analysis is required to include at least primary energy consumption (E-value), energy certificate and room temperature constancy during summer time. In addition to these, it is also possible to use BIM-based energy analysis in calculating heat loss balancing and dimensioned heating capacity, which are needed in the subsequent parts of energy survey. After building permit is granted, the project moves forward to (5) **detailed design**. If the changes made in the design during this phase potentially have considerable effects on comfort or energy performance, then energy analysis needs to be updated as well. During the (6) **construction phase**, there might be some further changes in the design, depending on the choices made by the contractor. At the end of construction phase, the energy consumption target for the building is calculated, while taking possible changes into account. Once the construction is complete, begins a phase called (7) **commissioning and warranty**. As the building is in actual use, better understanding of the building energy performance is obtained. In the light of this better understanding, the energy consumption target is updated if needed. Also, achieving indoor environment comfort requirements are verified during this phase. Finally, during (8) **operations and maintenance** (O&M), the energy and comfort performance of the building is monitored. [11]

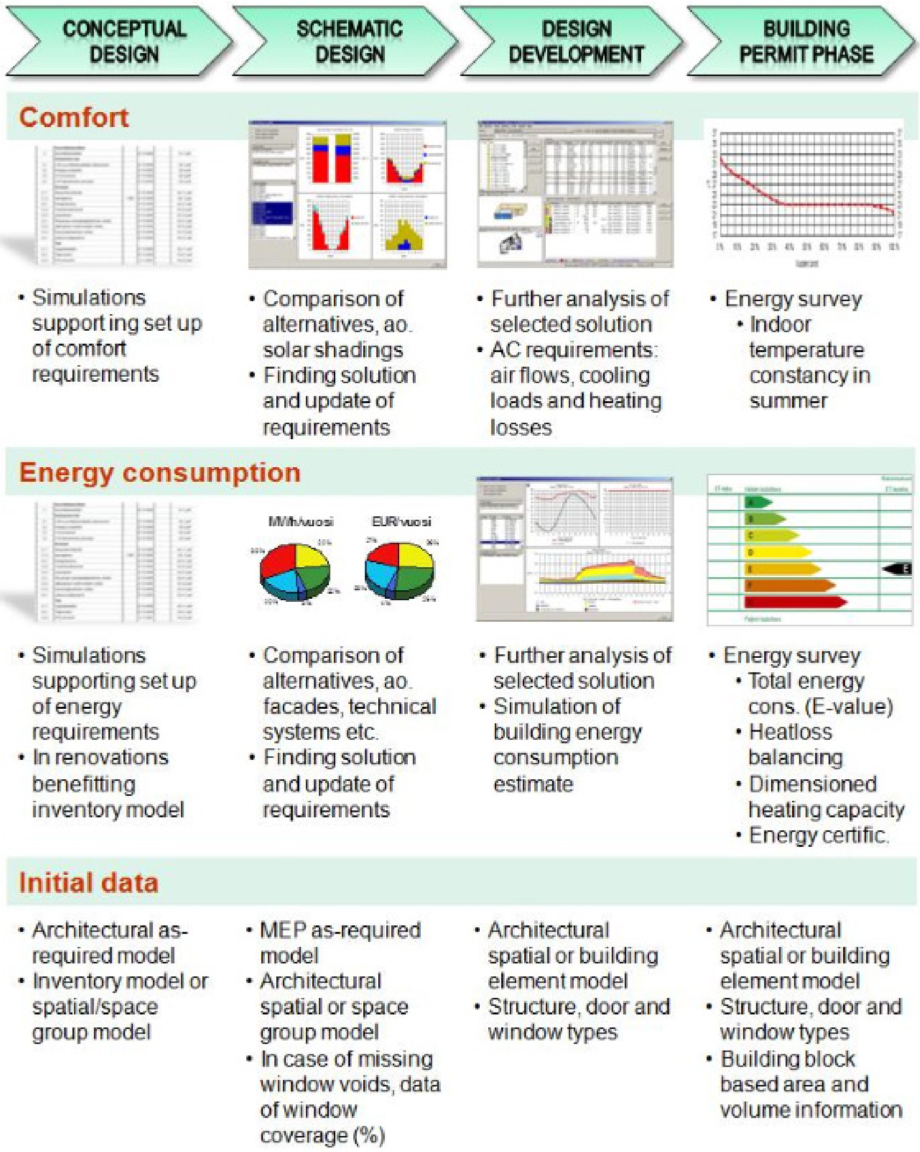


Figure 2.1. Potential ways to utilize energy analyses during all project stages, part 1/2. [11]

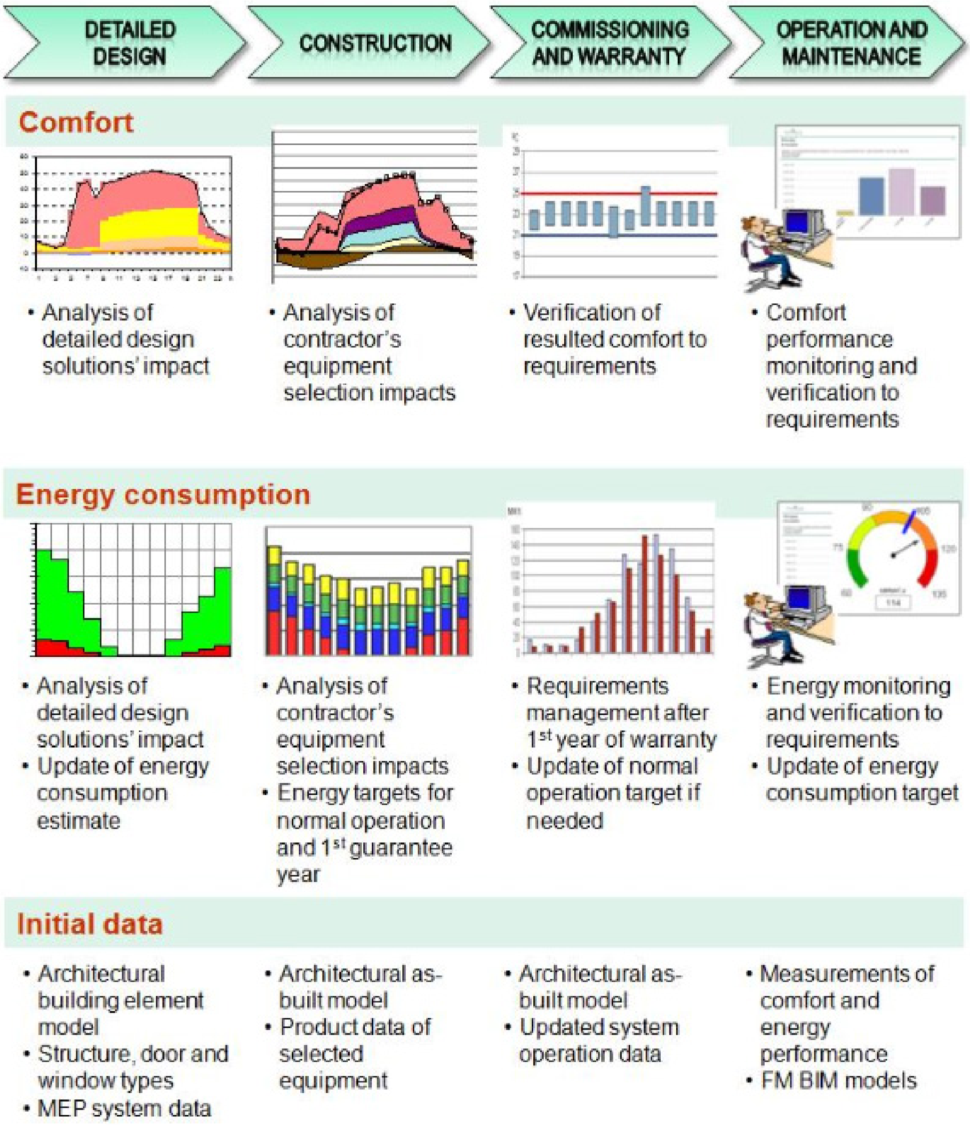


Figure 2.2. Potential ways to utilize energy analyses during all project stages, part 2/2. [11]

From Figure 2.1 and Figure 2.2 can also be seen that the data richness required from the BIM model increases as the project advances. Inventory model, which is used in retrofitting projects, is a model of the current state of the building or buildings. It is used in analyzing the building's current energy performance and for comparing different design solutions [11]. Spatial model consists of walls and the spaces they define. In order to use the spatial model for energy simulations, it is in most cases required to model also windows in a simplified way. The total area of windows is more important than the shape or location. Later during the project, building element model is created by adding building elements into the spatial model. The accuracy and the amount of information added to the model increases as the project advances. However, as the model becomes more complex, there can often be compatibility difficulties with different analysis software, including energy analysis. These difficulties can be avoided by creating a simplified version of the model for these analysis purposes. [23] Once the construction is complete, architectural as-built model is created, which is a representation of the actual building. Finally, facility management (FM) models are created for operation and maintenance purposes. [11]

Even though BIM utilization has been possible for a rather long time, some serious challenges still exist. One of these problems is the interoperability issues in transferring data from the BIM model to an energy analysis program. Another issue is defining the required information content for energy analyses. Therefore, in COBIM part 10 there is also described requirements for energy analysis programs and for data transfer. For energy analysis programs, two requirements are presented. The first one is that the program can import Industry Foundation Classes (IFC) files of version 2x3 or newer. [11]. The IFC file format is the only open, ISO-certified, three-dimensional and object-oriented exchange format used by BIM [24]. The second requirement for energy analysis programs is that they are capable of dynamic calculations. The properties required from dynamic calculation tools are presented later in Section 2.2.1. In current Finnish building energy regulations [25], in addition to dynamic calculation, the energy calculation program also has to be validated by SFS EN, CIBSE or ASHRAE standards. In COBIM [11], it is recommended that the program has been accepted by the Nordic Energy validation as well.

In Figure 2.3 is presented a simplified energy analysis process and the required exchange of information at each phase. The abbreviation MEP stands for mechanical, electrical and plumbing services. BIM-based data exchange is only required for architect's model. It is recommended also for architectural and MEP requirements, as well as for MEP service areas, but document-based data transfer is sufficient for these purposes. For the outputs of the energy analysis, there are no requirements, but again BIM-based data exchange is recommended. [11]

The architectural BIM model is the most important initial data required in BIM-based energy analysis. The data exchange should be based on IFC file format. Additionally, the IFC file is required to include two different views defined in the IFC standard: coordination view and space boundary add-on view [11]. Coordination view combines architectural, mechanical and structural BIMs into one model, which improves collaboration and information exchange between designers of different disciplines [26]. Space boundary add-on view is important in thermal calculations. It includes processing of space boundaries and other requirements for spaces, zones and thermal properties of elements [27]. Space boundaries are divided into two levels. 1st level boundaries are not influenced by what is on the other side, whereas 2nd level boundaries are influenced by adjacent spaces [28]. More detailed information about the space boundaries can be found in IFC implementation guide [28].

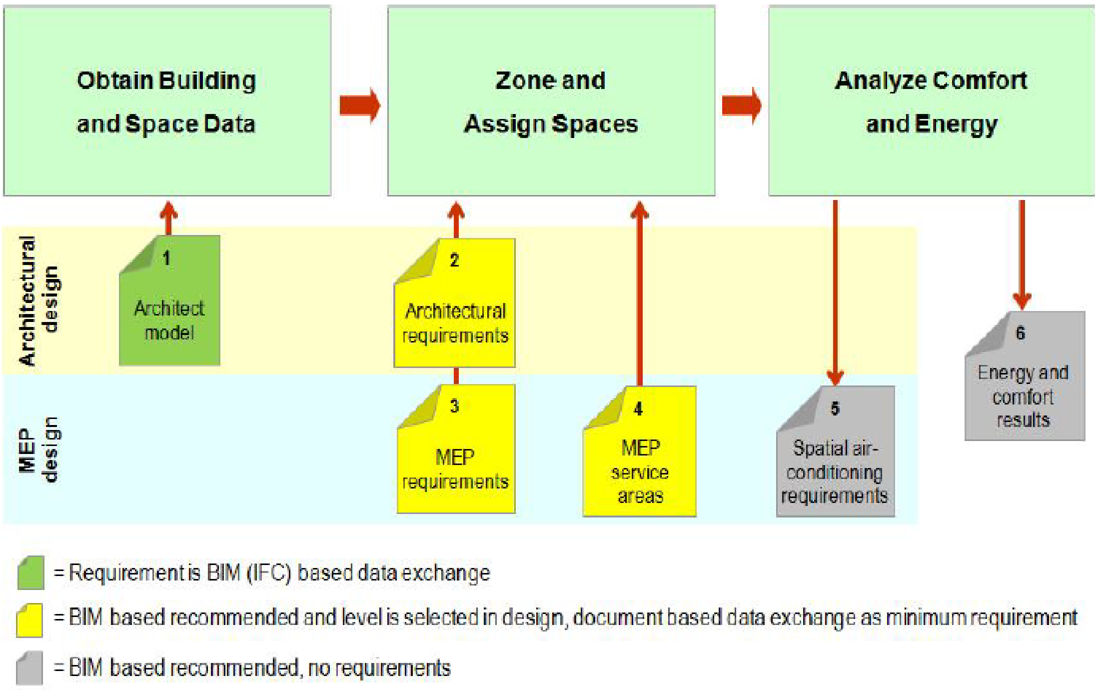


Figure 2.3. Simplified energy analysis process and related information requirements in COBIM. [11]

2.1.3 BIM in retrofit projects

Building retrofit projects include the same phases as constructing new buildings. The largest and most significant decisions are made already in the early conceptual design phase, similar to new buildings. Conceptual design includes gathering initial information about the building, determining needed repairs and evaluating possible retrofit solutions. An important key characteristic for retrofit projects is that as more information about the building is acquired, the designs often have to be altered accordingly. [29] BIM utilization in retrofitting projects is still rare, mainly due to the challenges in data collection and in creating the BIM model [15]. Nevertheless, the use of BIM in retrofitting projects have been found beneficial, even though the usefulness of creating a BIM model has to be assessed case specifically [30].

The BIM model of the starting situation is known as the inventory model. COBIM part 2 [31] addresses the creation of the inventory model and sets many requirements, as well as provides extensive guidelines for this task. In this document, the inventory models are divided into three levels: level 1 spatial model, level 2 building element model and level 3 building element model. The higher the model level, the higher are the requirements set for its creation. The model is complemented to higher levels as the project advances. Level 1 spatial model is used as a source of data for project planning and surveys. Level 2 building element model is the basic level of the inventory model, and it is needed after the project planning phase in the making of schematic level project plans. Level 3 building element model differs from level 2 by its higher level of detail, and it is required only for geometrically complex objects. [31]

In his master’s thesis, Helander [32] assessed the alternatives of utilizing BIM to manage initial information in building retrofit projects. He concluded that there is a need for two separate inventory models: a building frame model to provide exact dimensions of the structures and a space model for managing the building information. These models should be created in three different phases of the project, which are presented in Figure 2.4. In the first phase, a space model would be created based on existing drawings. In the second phase, the building frame model is created and the space model is complemented with additional information. In the third phase, the models are again complemented with additional information, if it has been obtained through measurements and surveys. Multiple phases should be used, so that the models can be of benefit already at the beginning of the project. However, during these phases, the need for a model should always be evaluated before creating these models. Also, the models should be created in a way that nothing needs to be done twice and only necessary elements are modeled. Since the models should be created and used as early in the project as possible, the early models cannot contain all the information that is needed. Thus, the most important thing is to document the assumptions and levels of accuracy that were used in the creation of the models. This way it is easier to cope with missing information and divide the responsibility between the stakeholders. [32]

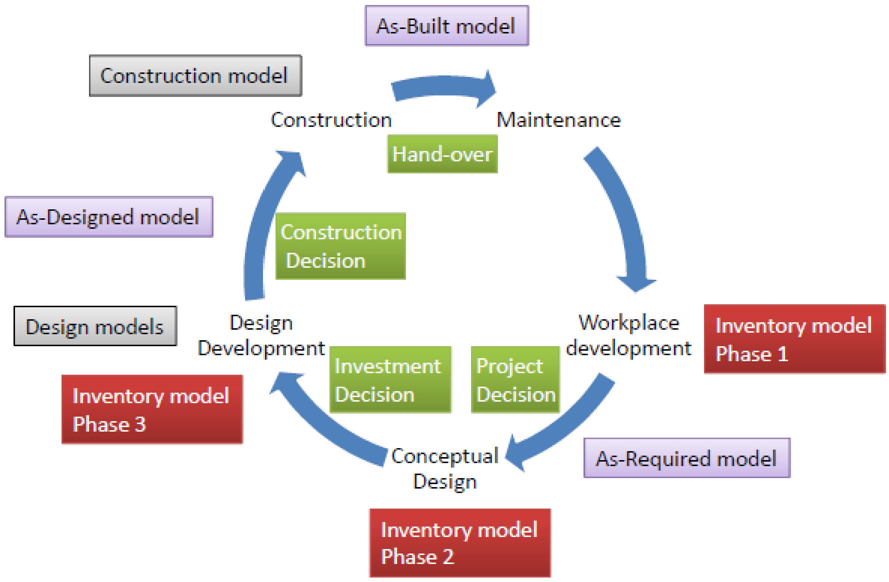


Figure 2.4. The three phases when inventory models should be created in renovation projects. [32]

Helander also made conclusions about the benefits of utilizing BIM in retrofit projects. The first benefit is the improved control and management of data, which results in up-to-date and accurate information. The second benefit is that BIM utilization provides a quicker start to projects. The third, and also the most important benefit in the framework of this thesis, is that BIM utilization allows early energy simulations. This is a significant benefit, because the most important and effective decisions concerning the energy efficiency and sustainability of the building are usually made already in the initial project stages. [32]

Volk et al. [15] made a literature review of over 180 recent publications on BIM utilization in the existing building stock and evaluated the future research needs. The focus of this review, however, was only on maintenance and deconstruction stages, and not on actual retrofit design. In this article, it was concluded that despite the numerous potential functionalities of BIM in existing buildings, its implementation is yet scarce. Moreover, its utilization is mainly focused on recently build buildings that already have BIM rather than older buildings without BIM. The reason for this can be explained by the many challenges of using BIM in existing buildings. Volk et al. identified three major challenges and areas of research needs in their review, all of which are informational issues. The first challenge is the difficulties in collecting the required data and in the creation of the BIM model. New automated techniques for collecting geometrical and thermal data for BIM creation are needed to overcome this challenge. [15] More detailed information about the data collection techniques and appliances can be found in Stjelja's thesis [17]. The second challenge is the manual work needed to update and maintain the information in the BIM models during the operational years of the building. To cope with this issue, building monitoring should be integrated into the BIM models in order to keep BIM information automatically up-to-date. The third major challenge is the handling and modeling of uncertain data related to retrofitting projects. Despite these challenges, the future of utilizing BIM in the existing building stock seems promising. Volk et al. predict that the trends of increased digitalization and automation as well as the large size of the existing building stock and tightening sustainability requirements will stimulate the implementation of BIM in existing buildings. In addition, new emerging technologies, such as mobile BIM devices, semantic web technologies and cloud computing, should make its implementation easier. [15]

2.1.4 Level of detail and level of development

BIM can be used throughout the whole lifecycle of a building - from conceptual design to operation and maintenance. During this lifecycle, the model is used for different functionalities, which affects the information richness and accuracy that is required from the model. To standardize the level of information, the American Institute of Architects (AIA) developed a specification called 'level of development' (LOD). The purpose of the specification is to help practitioners specify and communicate more clearly about the content and reliability of building information models throughout the construction process. This specification divides the development stage of the model elements into six levels. They are presented in Table 2.1 along with their definitions and interpretations. When designing new buildings, LOD increases as the project advances. [33] In retrofitting projects, the LOD depends on the functionalities needed [15]. In order to further explain the LOD framework and standardize its use, BIMForum has published a specification introduction [34] with more detailed description. It emphasizes that LODs are not defined by design phases, even though LODs can be used to define certain milestones in a project. Also, this specification states that there exists no such thing as an "LOD### model", because usually at different design phases the model has elements of different LOD. However, certain LODs are often a part of the contract documents in projects where BIM is utilized [35]. The required LODs vary in different projects, but Figure 2.5 gives a suggestive idea how the LOD increases as the project advances.

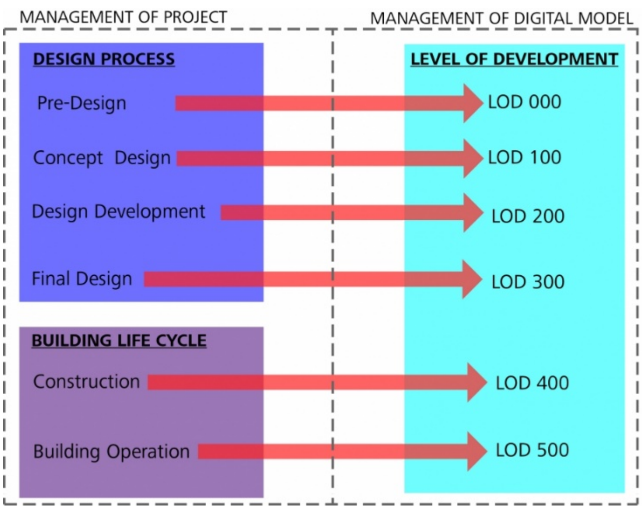


Figure 2.5. Example of levels of development during a construction project. [35]

Table 2.1. Level of Development definitions [33] and BIMForum interpretations [34].

LOD ###	Definition *	BIMForum interpretation
LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.	LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate.
LOD 200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.	At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. **Any information derived from LOD 200 elements must be considered approximate.**
LOD 300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.	**The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.**
LOD 350	The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.	Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
LOD 400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element	An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. **The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.**
LOD 500	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements	N/A

** Definition from the AIA's most recent BIM protocol document G202–2013, Building Information Modeling Protocol Form.*

There has been confusion about what LOD levels mean, partly because the same abbreviation is used for slightly different specification called 'Level of Detail'. They can be seen quite often used incorrectly as synonyms, even in scientific papers. Level of detail is a measure of the quantity of detail that is included in the model element, whereas level of development is a measure of how definitive and thought through the attached information is [34]. In other words, level of detail only describes the quantity of information, and level of development is a degree of how reliable the attached information. To make things even more complicated, also terms 'level of information' and 'level of definition" are used.

McPhee wrote a blog article [36] about LOD, in which is clarified the difference between level of development and level of detail by using a chair as a simple example. In this article, it is emphasized that level of development is an indicator of how seriously the information can be taken, but not automatically a measure of the quantity of information. Neither is it a measure of the accuracy of graphical presentation, as it is sometimes mistaken. The purpose of level of development is to tell other project members what information represented by a BIM element can be reliably used. On the other hand, level of detail is a measure of the amount of information added to an element, with the assumption that all provided information is reliable. This difference can more easily be understood from Figure 2.6 and Figure 2.7, in which level of development and level of detail is illustrated using a chair as an example. It is important to note, that in both figures only the data in red font is reliable. When using level of development, the graphical presentation at LOD 100 can be as detailed as in LOD 500. The difference is, that in LOD 100 it is only known for certain that the element is a chair, but in LOD 500 all the added information can be relied upon with certainty. This means, that a certain chair from a manufacturer could be used at LOD 100, but this particular chair would not necessarily be the one that is actually going to be used, as illustrated in Figure 2.6. In terms of level of detail, the graphical presentation evolves as the level of detail increases, as shown in Figure 2.7. First, only a 2D symbol of a chair is used. As more information is fixed, the graphical presentation is defined accordingly. [36]

Even though it is important to realize the difference between level of development and level of detail, it cannot be argued that they are closely related to each other. A certain level of development cannot be achieved without a certain amount of information (level of detail). In order to avoid further confusion, McPhee suggests that the abbreviation LOD should be used for level of development and some other term for level of detail. For example, AEC (UK) BIM Protocol [37] uses a term “grade”.

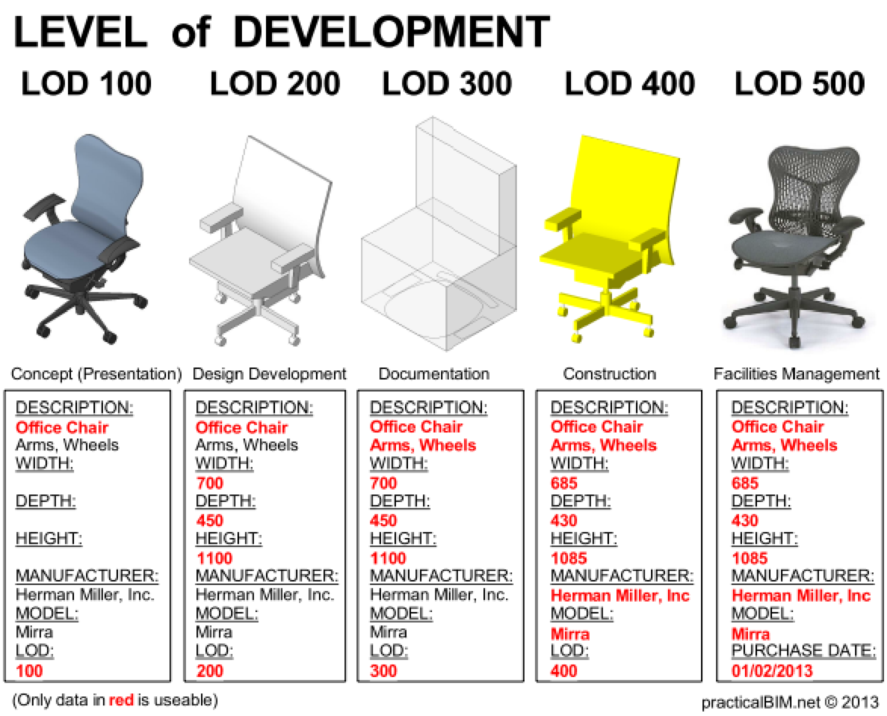


Figure 2.6. Illustration of level of development using a chair as an example. Note that only data in red font is useable. [36]

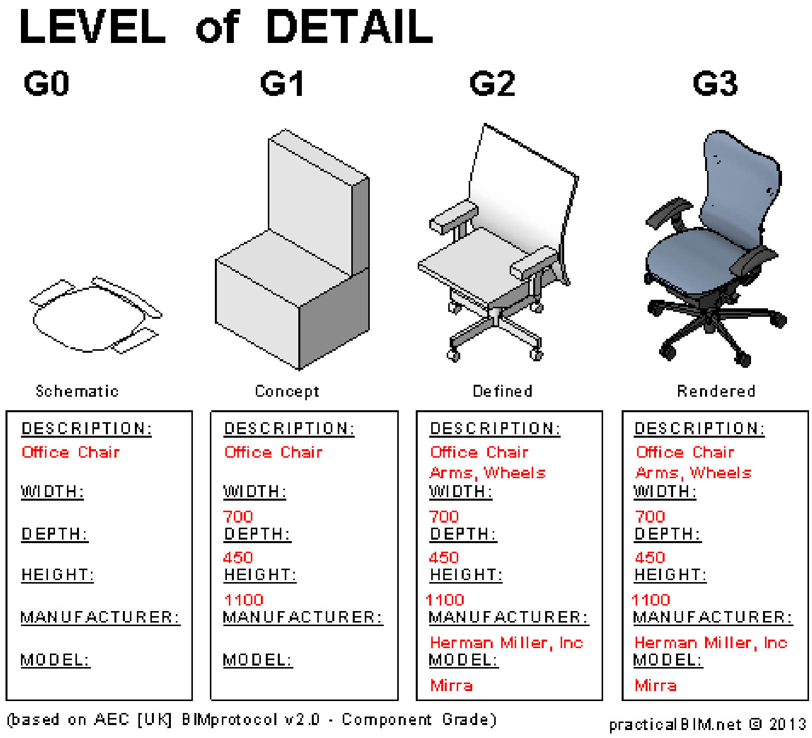


Figure 2.7. Illustration of level of detail using a chair as an example. [36]

One of the many definitions for level of detail is given by CityGML, which is an open data model based on Extensible Markup Language (XML) format and is used for storing and exchanging virtual 3D city models. CityGML characterizes the level of detail with five consecutive levels, LOD0 being the coarsest and LOD4 the most accurate (Figure 2.8). On a city level, LOD0 is only a landscape which can be supplemented with an aerial image or a map. LOD1 represents buildings only with simple blocks, while LOD2 includes roof and surface elements. LOD 3 resemble architectural models with detailed exterior wall and roof structures, windows and balconies. The most accurate level, LOD4, includes also interior structures and furniture. Additionally, these LODs are characterized by varying accuracies and minimum dimensions of objects. The absolute 3D point accuracy for LOD1 is 5 meters. In the subsequent LODs the required accuracies are: 2 meters in LOD2, 0.5 meters in LOD3 and 0.2 meters in LOD4. [38]

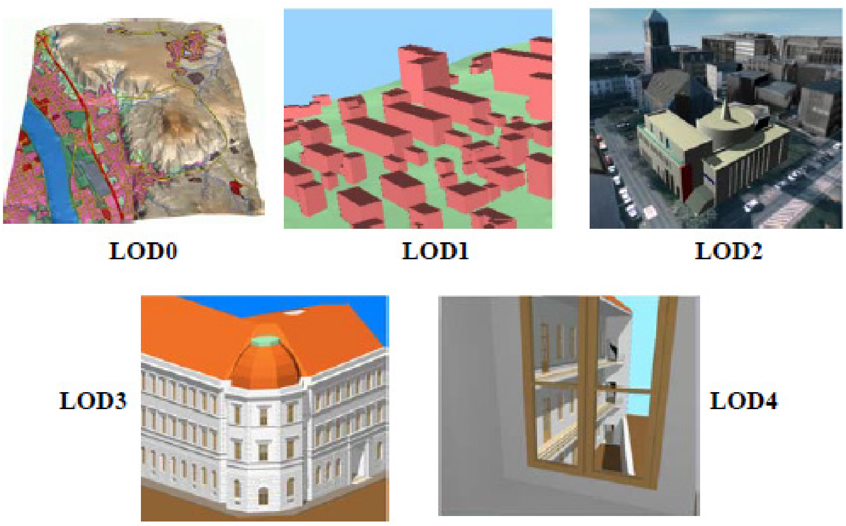


Figure 2.8. The five levels of detail defined by CityGML. [38]

The levels of detail from LOD1 to LOD4 for one individual building model are illustrated in Figure 2.9. LOD1 building model is just a simple block representing the building footprint. In LOD2 model, a pitched roof is added on top of the block. LOD3 building model includes also exterior doors, windows and a chimney. In LOD4 model, the building is completed with rooms formed by interior walls, as well as stairs and possibly furniture. [38]

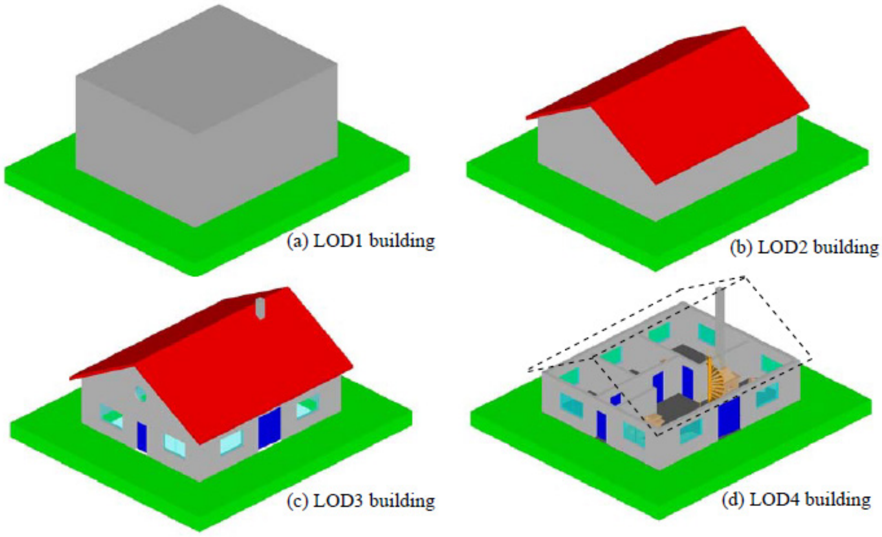


Figure 2.9. CityGML LOD1 – LOD4 for individual building model. [38]

2.2 Dynamic energy simulation

The previous section described BIM and its utilization in energy analyses and retrofit projects. One significant benefit of using BIM in energy analysis is that it allows easier use of accurate dynamic energy simulations, as the BIM model can be used as a data source for many energy simulation tools. In this section, dynamic building energy simulation (BES) is discussed in more detail.

BES forms an essential component of most energy analyses. It is used for simulating the energy flows inside a building and between its environment under given circumstances and functional requirements. Also, the term "building energy modeling" is used for predicting building performance with the help of simulations. Usually, BES focuses on the energy performance and thermal comfort of buildings. [10] Energy simulations allow designers to predict building performance under certain criteria and make it possible to compare different design solutions more accurately [39]. While this is useful for designing new buildings, it is also useful in retrofit projects. Currently, hundreds of different software programs are available for energy simulation and analysis. They can be categorized in multiple ways, but one common way is to divide them into dynamic and steady-state simulation models. Steady-state models are simple to use and require little computational capacity. However, they do not take dynamic (time dependent) changes into account, such as fluctuating weather conditions, thus making them less accurate.

Since dynamic calculation is required in COBIM [11] and in Finnish energy regulations [25], this section focuses on dynamic energy simulations. Section 2.2.1 justifies the need for dynamic energy simulation in energy analyses and describes their utilization in general. Section 2.2.2 gives an overview of the input data requirements for dynamic energy simulations. Finally, the simulation software RIUSKA, which is used in the piloting part of this work, is described in Section 2.2.3.

2.2.1 Role in energy analyses

A building is a complicated system in terms of energy, as it is characterized by a large number of parameters, including the thermal properties of the envelope components, weather, operating schedules, as well as ventilation and air infiltration rates. It has always been a challenge to achieve high indoor air quality, while maintaining costs at an acceptable level. With the advent of tight building regulations, a certain energy efficiency is also required, which makes achieving all these targets even more demanding. Moreover, the amount of available materials and systems is constantly increasing, which has led to an increasing variety of possible design combinations. In addition to the large number of parameters, building energy systems consist of multiple subsystems, such as heating and cooling, ventilation, lighting and other electrical appliances. Adjusting one system can have non-trivial effects on other systems. In short, the energy systems of buildings and their requirements have become so complex that it is almost impossible to find an acceptable design solution based only on expert knowledge and educated guesses. Therefore, building energy simulations are needed and are becoming an increasingly important part of the design process for buildings. [8, 10]

Even though steady-state models are fast and relatively easy to use, they can be rather inaccurate due to several issues. The main issue is that buildings always have some amount of thermal mass allowing energy to be stored and released in the structures, which cannot be taken into account with steady-state models. Moreover, the outdoor and indoor environment clearly vary with time. In addition to variations in weather, also the activity inside the building varies with time, and thus for example internal gains and heating/cooling demand are constantly changing. Using dynamic simulation, these phenomena can be taken into account in order to obtain more reliable results. However, dynamic simulation tools have a drawback of making the simulation model much more complex. This causes them to require more time in creating the simulation model and more computing power. In addition, they require a more experienced user, since the user is usually the greatest possible source of error when using dynamic simulation tools. Moreover, they require more detailed input information, which can be difficult to obtain, especially in retrofit projects. [40] The following five properties are required of dynamic simulation tools: (1) energy stored in structures is taken into account, (2) calculations have to cover a whole year, (3) the maximal time step used is one hour, (4) weather data corresponding to building's location is used and (5) internal loads and their time profiles are taken into account [11].

There are three main modeling approaches available for building energy modeling, which are the white box model, the black box model and the grey box model. White box models, also known as forward models, are purely based on physics and equations. Black box models are purely empirical, and grey box models something in the between. The white box modeling approach utilizes detailed physics based energy and mass transfer equations to model the building behavior. Thanks to these detailed equations, they are capable of dynamic simulation and can produce accurate results. However, this kind of models are time consuming to develop and solve. Nevertheless, a wide array of mature white box building energy simulation software have been developed and widely used, such as EnergyPlus and TRNSYS. [41, 42]

The white box modeling approach from the energy analyst's point of view is presented in Figure 2.10. The procedure described in this figure, however, is not universal, but has been followed in many research articles. [41] In addition, the general data flow and a simplified procedure utilized in white box modeling is presented in Figure 2.11. First, the needed input parameters about the building and its systems have to be obtained and inputted in the simulation software. Using these input parameters, the simulation engine simulates the building operation with the physics based equations it has been programmed with. As a result, the simulation engine produces energy performance indicators as outputs, such as heating and electric energy consumptions. [42]

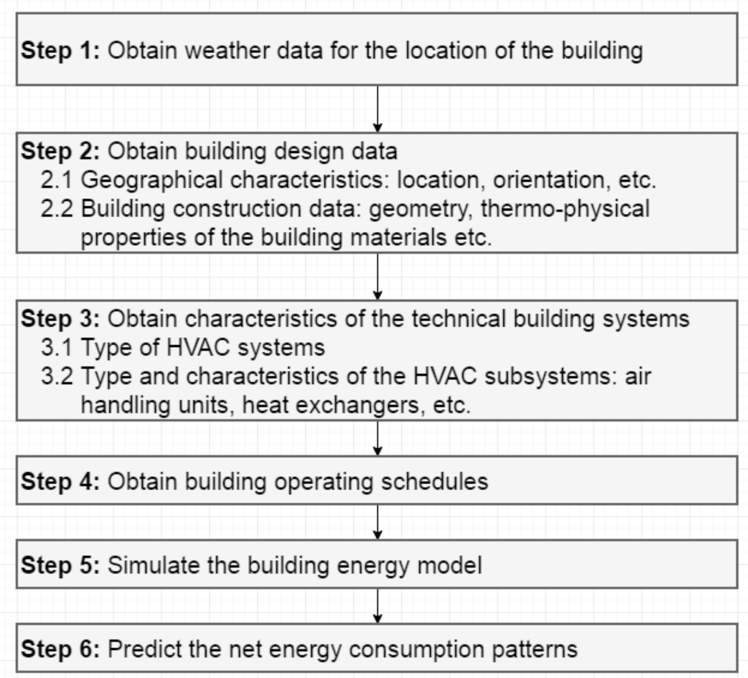


Figure 2.10. The forward approach of building energy modeling divided into six steps. [41]

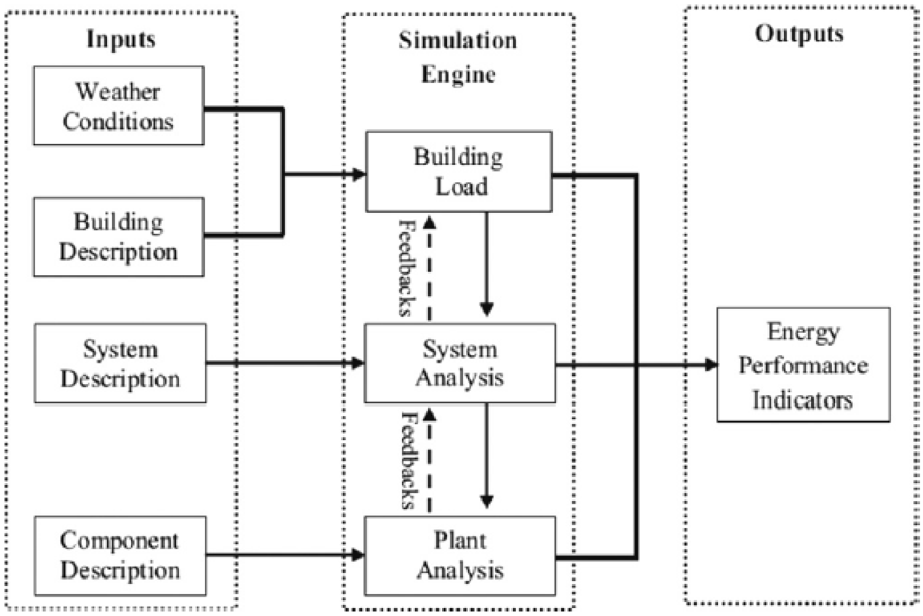


Figure 2.11. The general data flow and simplified simulation procedure used in the white box modeling approach. [42]

2.2.2 Input parameters for energy simulation

The required input parameters for building energy simulations depend upon many things, such as which simulation tool is used and what is the purpose of the simulation. In his master's thesis, Idman [13] reviewed several case studies about the ecosystems of building energy simulations, and made conclusions about the general grouping and significance of the input parameters. This section is partly based on Idman's thesis and partly on the writer's previous experience as well as the experience gained from the making this thesis.

The numerous input parameters needed for simulating energy use of buildings can be divided into design parameters and scenario parameters. Design parameters are variables that can be determined by the designer, while scenario parameters cannot be influenced by the designer. The parameters can be further divided into subgroups, such as geometry related parameters and structural parameters. This is not a universal course of action, as some sources handle the parameters as a single group. [13] In addition, the significance and the nature of these parameters can be different for varying building types.

In general, the energy performance of a building depends mostly upon parameters within six groups: (1) geometry of the building, (2) properties of the envelope elements, (3) properties of the HVAC systems, (4) internal loads, (5) building schedules, as well as (6) the surrounding environment. If calculation of costs is included in the analysis, then the seventh group is (7) economic parameters. Again, this is not a universal way of grouping the parameters, but this kind of division was chosen as the most appropriate for this work. These groups and some of the most important input parameters are presented in Table 2.2.

The first group, geometry of the building, defines the thermal zones and spaces in the building. The location and properties of the space elements have to be defined, because all other data is related directly to these elements. The building is usually divided into rooms, which have varying internal loads and requirements. Also, the orientation angle of the building is included in this group. [13] If BIM is used in the simulations, then all the geometry related information is obtained from the BIM model. By defining the use purpose, requirements and occupancy information for each space allows the energy efficiency and comfort to be analyzed more precisely in the whole building [13].

The second group, properties of the envelope elements, includes the needed parameters to determine the properties of the structural elements and windows. For windows, the most important parameters are U-value, g-value, size and orientation. U-value is a measure of the overall thermal resistance of a building element. The higher the U-value is the more heat is conducted through the element. On the other hand, g-value is a measure of how much solar energy is transmitted through the glass. It is given as a percentage, meaning that a window with a g-value of 100% transmits all the solar energy radiated on it and a window with a g-value of 0% does not let any solar energy past it. Glazing has high impacts on many aspects of building performance, such as heat losses, lighting, comfort and overheating [13]. The structural elements include exterior and interior walls, as well as base floors, intermediate floors and roofs. The most important parameters to characterize these elements are their U-values and heat capacities. The U-values of these structures affect the heat losses through the envelope, while the heat capacities affect the amount of heat stored in the structures. In addition, the air infiltration rate of the building is included in this group.

The third group, HVAC systems, can contain a very large number of parameters. These parameters are mostly related to ventilation, heating and cooling of the building, such as set point temperatures, control curves, electricity demands and efficiencies. These parameters depend upon the types of HVAC systems chosen for the building. For the ventilation of the building, also room specific air flows need to be determined. HVAC systems have a high impact on the comfort level, as well as on the energy consumption.

The fourth input parameter group, internal loads, include heat loads from lighting, equipment and people. These internal loads are usually inputted as wats per square meter [W/m^2] and their values depend upon the use purpose of the space. The heat load from lighting can be affected with the design. On the other hand, the heat loads from equipment and especially from people are in most cases uncertain, since it is difficult to estimate how many people will use the building and what kind of electric appliances will be used. Thus, these parameters can be treated as scenario parameters in the energy analysis.

The fifth group, building schedules, is closely related to the fourth group. This group determines the schedules during which the building is used, and the utilization rates during those hours. Utilization rate is a measure of how much people is using the building, thus affecting the usage of lighting and equipment. Therefore, the internal loads are dependent upon the schedules and utilization rate of the building. In addition, the control of the HVAC systems is affected by the schedules. For example, ventilation is usually turned off when the building is not used. In most energy simulation software, the schedules have to be determined separately for internal loads and HVAC systems. Additionally, schedules for other features, such as shading rate of window blinds, can be determined. It should be noted that the internal load schedules and utilization rates are in many cases uncertain, and thus they can be considered as scenario parameters. The schedules of the HVAC systems, on the other hand, can be affected with the design.

The sixth group, the surrounding environment, determines the setting in which the building is located. One significant phenomenon affecting the energy consumption of buildings is the weather. Information about the weather is usually inputted in the simulation software as a single file, that contains hourly data for outdoor temperature, relative humidity, wind speed and direction, as well as for solar radiation. In energy simulations, weather is not usually considered as a variable, but instead it is assumed to remain constant while other input parameters are varied. Usually, test reference year (TRY) weather files are used in the simulations. These are weather files created by meteorological institutes that define typical weather conditions in different geographical locations. Since the designer cannot in any way affect the weather, all the weather related parameters are clearly scenario parameters. In addition to weather, also the shading caused by the surrounding buildings and vegetation can have significant effects on the heating and cooling demands of buildings.

The seventh group, economic parameters, is also consisted of uncertain scenario parameters. The most important parameters are interest rate, inflation rate and escalations. Energy price escalation describes the relative change in energy prices with respect to common inflation. These parameters do not affect the energy performance of buildings in any way, but they can have a significant effect on their life cycle costs.

Table 2.2. Input parameters of building energy simulations divided into groups.

Group name	Example input parameters	Parameter nature
Model geometry	Heated net room area [m^2]	Design parameter
	Volume [m^3]	
	Exterior wall area [m^2]	
	Roof area [m^2]	
	Orientation angle [°]	
Envelope & glazing	Exterior wall U-value [W/m^{2}K]	Design parameter
	Roof U-value [W/m^{2}K]	
	Ground slab U-value [W/m^{2}K]	
	Window U-value [W/m^{2}K]	
	Window g-value [%]	
	Infiltration rate n_{50} [1/h]	
HVAC systems	Ventilation rate [dm^3/(sm^2)]	Design parameter
	HRU efficiency [%]	
	Specific fan power of AHUs [W/(ls)]	
	Cooling set point [°C]	
	Heating set point [°C]	
	Heating distribution system efficiency [%]	
	Domestic hot water heat demand [kWh/(m^{2}a)]	
Loads	People heat load [W/m^2]	Scenario parameter (but can partly be affected with design)
	Equipment heat load [W/m^2]	
	Lighting heat load [W/m^2]	Design parameter
Schedules	Schedules and utilization rates of internal loads	Scenario parameter (but can partly be affected with design)
	Operational schedule of ventilation system	Design parameter
Surrounding environment	Weather file	Scenario parameter
Economic	Interest rate [%]	Scenario parameter
	Energy price escalation rate [%]	

2.2.3 RIUSKA

The energy and comfort simulation software RIUSKA is based on the internationally acclaimed DOE 2.1E simulation program. It has been developed by Granlund in collaboration with the developer of the DOE program, which is Lawrence Berkeley National Laboratory. [43] RIUSKA has passed the Nordic Energy validation, which is recommended in the COBIM [11].

RIUSKA utilizes BIM in the calculations and supports the IFC format for both importing and exporting the model. It is a very versatile software, since it can be used for many different purposes. Like most energy simulation software, it can be used to ensure compliance with the regulations and the project objectives, calculate estimated consumptions and to simulate indoor temperatures both in the summer and winter. In addition, it can be used for the sizing of technical systems, such as cooling [43], which is currently one of the most common purpose of using RIUSKA at Granlund.

Nevertheless, what makes RIUSKA special, is its parametrized simulation feature. This feature allows the user to choose value ranges for the input parameters, based on which a large number of cases are calculated in one simulation round. The pop-up window of the parametrized simulation is presented in Figure 2.12, in which are listed the parameters that can be parametrized. For some parameters, such as all the envelope components, the range of values is determined choosing different types. RIUSKA has a default database for all the envelope components as well as for the schedules, which can all freely be modified. New construction types and schedules are easy to create as well. For other parameters, such as the internal loads, the parametrization is done by inputting minimum and maximum values for the range, and then defining the length of the step. It is also possible to parametrize other inputs outside this list by using different simulation cases. This means creating different simulation cases in RIUSKA, and then choosing them in the pop-up window (Figure 2.14) to be included in the parametrization. Once the parametrization of inputs has been determined, RIUSKA can either simulate all the possible combinations or a random sample of any size from this group. The amount of simultaneous simulations can also be chosen by the user, up to 16 simulations at the same time. The simulation results are saved to a CSV-file, which is automatically uploaded to the visualization website called the Key Point Analysis (KPA) tool. This visualization tool is described later in Section 3.3. This parametrized simulation feature allows easy and efficient comparison of different design solutions, as well as analyzing the energy performance of the building in different loading and weather conditions. This feature is also very beneficial for the utilization of sensitivity and uncertainty analyses, since they both require a large number of parametrized simulations.

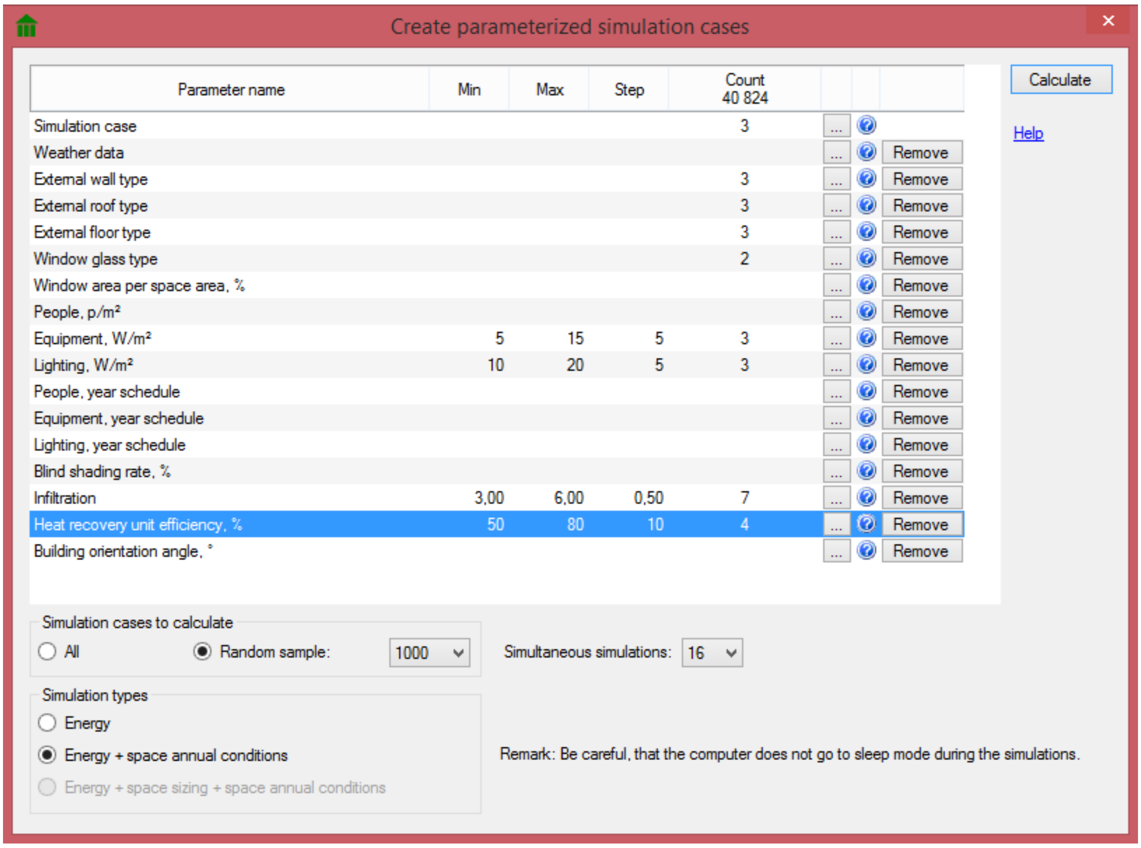


Figure 2.12. User interface for the parametrized simulation in RIUSKA.

2.3 Sensitivity and uncertainty analyses

Uncertainties play an important role in performing energy analysis of buildings. Many input parameters of the simulation model often cannot be known accurately, which is a problem especially in retrofit projects. These uncertainties should be taken into account in order to make justified design decisions [13]. This can be done by using sensitivity and uncertainty analyses. Both sensitivity and uncertainty analysis require a large number of simulations with varying input parameters. Thus, using a BIM-based energy simulation software with a parametrization feature, such as the previously presented RIUSKA software, makes utilization of these analyses significantly easier.

This section provides an overview of sensitivity and uncertainty analysis utilization in building energy analyses. Section 2.3.1 presents the definitions and typical implementation steps of these two analyses. Section 2.3.2 discusses different ways of determining the variations of the input parameters. Section 2.3.3 discusses the utilization of these two analyses in building energy analyses. Finally, a brief overview of different methods and visualizations is given in Sections 2.3.4 and 2.3.5.

2.3.1 Definitions and implementation steps

Sensitivity and uncertainty analyses are sometimes incorrectly thought to be the same thing, but there is a clear difference between them. They are, however, linked together and work best when used together. Sensitivity analysis is used to determine the model's sensitivity to changes in input parameters, while uncertainty analysis is used to determine the probability distribution or the range (uncertainty) of the outputs. In other words, sensitivity analysis is used to find out which input parameters have the greatest influence in the variability of the outputs, and uncertainty analysis is used in determining the uncertainty of the output. The uncertainties in the outputs are caused by uncertainties in the inputs, which links these two analyses together. [44, 45, 46, 47]

The definition of sensitivity and uncertainty analyses is described mathematically in [48] as follows. Consider that the analysis results (outputs), vector $\boldsymbol{y}$, is a function of uncertain inputs, vector $\boldsymbol{x}$:

$$\boldsymbol{y}(\boldsymbol{x}) = [y_1(\boldsymbol{x}), y_2(\boldsymbol{x}), \dots, y_{nY}(\boldsymbol{x})] \tag{2.1}$$

$$\boldsymbol{x} = [x_1, x_2, \dots, x_{nX}] \tag{2.2}$$

Consequently, uncertainties in the inputs $\boldsymbol{x}$ cause corresponding uncertainties in the output $\boldsymbol{y(x)}$. Now, there are two questions that require answers: (1) What is the uncertainty in the output vector $\mathbf{y(x)}$?, and (2) How significant are the separate components of $\boldsymbol{x}$ (x_1, x_2, etc.) in causing the uncertainties in $\mathbf{y(x)}$? Uncertainty analysis aims to find an answer to the first question, while sensitivity analysis aims is to answer the second question. [49]

Sampling-based sensitivity and uncertainty methods are widely used, also in building energy simulations [13]. There is available a wide array of sampling-based methods, but their typical implementation for all purposes can be divided into four steps [49]:

1. Define probability distributions of input parameters
2. Generate a sample of input parameters based on the probability distributions
3. Run the sample through the calculation model to get results
4. Present the results of uncertainty and sensitivity analysis

Tian [16] described the implementation of sensitivity analysis especially in building performance analysis with the flow diagram presented in Figure 2.13. Uncertainty analysis was not considered in Tian's article, but the same implementation steps apply to uncertainty analysis as well. The first step, is to determine the variations of the input factors. The determination of these variations depends upon the parameters and research purpose of the sensitivity analysis. This will be discussed more in the next section.

After the input variations have been determined, the next steps are to create building energy models and run the simulations with varying input parameters. Most of the sensitivity analysis methods require a considerable number of simulations, from tens to thousands, in order for the results to be reliable. Therefore, it is recommended to use building energy simulation programs that allow automatically creating different input parameter combinations for parametrized simulations. Many simulation programs, such as EnergyPlus, ESP-r, TRNSYS and DOE2, have been used for sensitivity analysis. [16]

Once the simulations have been performed, the results need to be collected in order to run the sensitivity analysis. The results usually include a large amount of data, and automating the process should be considered. Running the sensitivity analysis itself usually does not require much time. [16] The final step is to present the sensitivity and/or uncertainty analysis results, which is covered in Section 2.3.5.

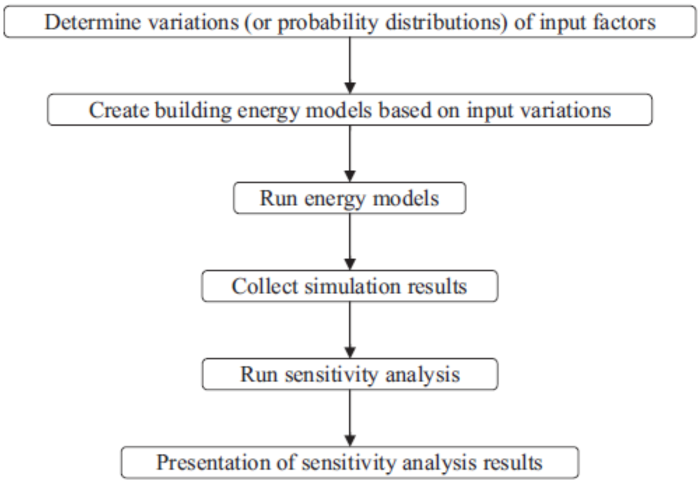


Figure 2.13. Typical sensitivity analysis implementation steps in energy analysis of buildings. [16]

2.3.2 Determining input variations

In order to get any results from sensitivity and uncertainty analysis, there needs to be variation in the input parameters. Therefore, the variations, or probability distributions, of uncertain input parameters have to be determined first. This is not a trivial task, and the possible variations should be considered carefully. According to Helton et al. [49] this is the most important part of sampling-based sensitivity and uncertainty analysis, as the distributions determine both the uncertainty in the outputs as well as the sensitivity to the inputs.

In the literature, there have been different opinions on how these distributions should be determined. Hopfe [47] uses normal distributions, which requires knowing the averages and standard deviations of the parameters. Estimations of standard deviations for some building parameters can be found from the literature. However, for most building parameters they are challenging to determine. On the other hand, Helton et al. [49] state that it is not advisable to try determine normal distributions for the input parameters. Instead, the distributions should first be based on rough estimations performed by experts. Then, the important input parameters can be identified by the sensitivity analysis, and the most important input distributions can be defined more precisely, if needed. This procedure was tested by de Wit et al. [50] in uncertainty analysis of building energy simulations, and yielded good results.

On the other hand, according to Tian [16], correctly choosing the input variations depends on the research purpose of the sensitivity analysis. In this thesis, there are two different cases considered: (1) analyzing the current energy use in an existing building and (2) analyzing various retrofit design solutions. In the first case, when the current state of the existing building is analyzed, it would be best to use normal distributions for most of the input parameters. The variables are likely to be constant for the building, but it is challenging to determine them accurately due to variations caused by many different factors. For example, the U-value of an existing building might vary because of natural degradation, material quality, maintenance etc. In the second case, where the sensitivity to different retrofit design solutions are analyzed, there are two kinds of variations: natural variations (e.g. degradation of materials) and design variations (e.g. different insulation thickness). More complicated methods, such as two-dimensional Monte Carlo method, could be used to account for both types of variation, but they require more computational power and are hard to interpret. Nevertheless, the effects of the design options are likely to be more significant, and therefore the simple solution is to disregard the effect of the natural variations. Then, uniform distributions for the design options should be used, because the design parameters can be considered to be equally probable. [16]

As a summary, expert driven or normal distributions should be used when analyzing the possible input parameter ranges of an existing building or scenario variables, and uniform distributions when analyzing different retrofit design solutions. However, in this work uniform distributions are used in every case, since it would be problematic to define means and standard deviations for the parameters. Moreover, the software used in this work is currently limited to taking a simple random sample of uniformly distributed parameters. In any case, the possible ranges need to be considered carefully, and try to avoid defining them too narrow or too wide, since the ranges have a great impact on the sensitivity and uncertainty analysis results. Also, it might be advisable to perform the sensitivity analysis iteratively, while defining the input ranges more precisely for parameters that proved to be important.

2.3.3 Utilization in building energy analyses and design

In energy analyses for building design purposes, sensitivity analysis results are used to guide the simulation process by identifying the parameters that have most significant impact in the energy performance of the building. This information can be used, for example, to narrow down the ranges of input parameters in the later simulations [13]. Furthermore, if the interactions and relative importance of the input parameters are known, it will be easier to achieve optimal building energy performance by properly selecting the design variables [51]. Additionally, sensitivity analysis has been used in many studies, including calibration of energy models, assessing the effect of climate change on buildings and building stock studies [16]. However, there exists no formal process for performing sensitivity analysis in building design, since the objectives of each study may be very different from each other [51]. Furthermore, Stjelja [17] introduced a way to utilize sensitivity analysis in the data collection phase of retrofitting projects, which is described later in Section 3.4.2. In building energy simulations, the effects of many parameters are linear and can easily be inferred. However, the relative importance of different parameters for different buildings types and design alternatives is not usually self-evident, making sensitivity analysis helpful.

Sensitivity analysis is not useful in comparing individual simulation cases, as it only points out the significant input parameters. On the other hand, uncertainty analysis results should be a part of the final decision making, as they provide useful information about the uncertainties of design options. [13] When performing uncertainty analysis, it is advisable to also perform sensitivity analysis in order to find out which parameters are the most responsible for causing the uncertainty. On the other hand, sensitivity analysis can be done without uncertainty analysis if the goal is only to find out the most significant parameters.

2.3.4 Methods

For uncertainty analysis, there is basically just one method to be used. This is calculating scenarios with different input parameters and then analyzing the spread of the results with different visualizations, functions and/or statistical numbers. The different uncertainty visualizations will be briefly covered in the next section. On the other hand, a wide array of different methods exists to perform sensitivity analysis and to analyze the generated output. This range of methods is reviewed here very briefly, while the method used in this work, regression method with Standardized Regression Coefficients (SRC), is described in more detail. The reason for choosing this method is explained later in Section 3.4.1 A more detailed review of the different sensitivity analysis methods is given for example in [47] and [16].

The sensitivity analysis methods can be divided into local and global methods. Local methods change only one parameter at a time and are used for determining the partial derivation of the output relative to the input. Global methods sample all the parameters simultaneously and are used for determining the uncertainty of a particular input parameter relative to the total output. Here, global means that the input parameters are varied over the whole value range they are given. [47]

Global sampling-based methods include regression methods, screening methods and variance-based methods. In building energy analyses, regression methods are the most commonly used for sensitivity analysis, because they are relatively easy to understand and fast to calculate. Unlike some local methods, regression methods do not require a base case to be determined, making them better suitable for most energy analyses. [16] When using regression method for sensitivity analysis, it is often necessary to perform Monte Carlo simulation, which means creating a random sample based on the probability distributions of the input parameters. Then, the sample is simulated, after which the results are processed and analyzed. Based on this dataset, an approximate equation is determined with regression analysis that can predict the output (e.g. heating energy consumption) as a function of the input parameters (e.g. wall U-value and window U-value). The form of the regression equation is:

$$y(x_1, x_2, \dots, x_n) = \beta_0 + \sum_{j=1}^{n} \beta_j x_j \tag{2.3}$$

where y is the predicted output value, x_j is the input value of design parameter j and β_j is the regression coefficient of parameter j. The regression coefficients already give some idea about how significant the input parameters are in respect to the output. However, these coefficients depend upon the units of the corresponding input parameters, which in building energy analyses do not have the same order of magnitude. For example, the building floor area can be 5000 m^2, while the wall U-value is 0,4 W/m^2K. Thus, the regression coefficients have to be normalized in order to be able to compare them to each other. [52] For this purpose, multiple different indicators can be utilized, such as Standardized Regression Coefficient (SRC), Partial correlation coefficient PCC, as well as their rank transformations SRRC and PRCC [16]. Of these indicators, SRC is used in this thesis. SRC is calculated for each input parameter separately with the following equation:

$$SRC_j(x_i, y) = \beta_j \cdot \frac{s_{x,j}}{s_y} \tag{2.4}$$

where $s_{x,j}$ is the estimated standard deviation of the input parameter (x_j) and s_y is the estimated standard deviation of the output (y). These SRCs can then be quantitatively compared to each other in order to assess the sensitivity of the model to these parameters. The higher the SRC value of an input parameter is, the more sensitive the model is to that parameter. [52] The SRCs can get values between -1 and +1. However, the sign only indicates to which direction the output changes when the input parameter is changed. In building energy analyses, the direction is usually well known beforehand, and thus it might be better to use absolute values to make the comparison of the SRC values easier.

It should be noted, however, that the standard deviation of a uniformly distributed parameter is directly proportional to the difference between its maximum and minimum values. [52] This means that the width of the input value range has a very high impact on the SRC values, making the determining of input variations the most crucial part of performing sensitivity analysis.

2.3.5 Visualization

Visualization is an important aspect of both sensitivity and uncertainty analyses. Regarding sensitivity analysis results, the most commonly used visualization is the bar chart. An example of such a chart is shown in Figure 2.14, which represents the sensitivity of annual cooling (blue bars) and heating (white bars) in some specific case. [47] The lengths of the bars indicate the SRC values of each parameter, which allows easy comparison of the relative significance of the parameters. In this example, infiltration rate seems to be the only parameter affecting annual cooling, and it has the highest influence on annual heating as well. As shown in this figure, it is possible to visualize the sensitivity of multiple outputs in the same chart with bars of different colors. In this example, the bars are horizontal, but vertical bars are often used as well.

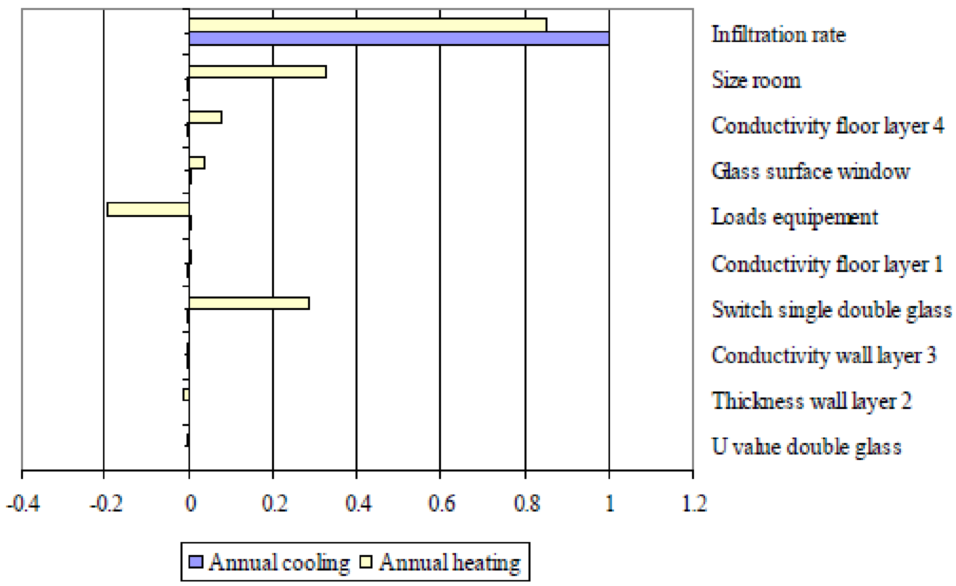


Figure 2.14. An example bar chart for visualizing sensitivity analysis results. [47]

Regarding uncertainty analysis, the applicable visualization methods depend upon what kind of uncertainty is being analyzed. For the visualization of single continuous numeric variable, there are three commonly used visualization methods: the probability density function (PDF), the empirical cumulative distribution function (ECDF) and the histogram. Examples of PDF and ECDF are presented in Figure 2.15, in which the uncertainty of Net Present Value (NPV) is visualized with both methods. The values in the PDF are not actual probabilities, but the probability that the variable gets a value in some certain range can be calculated with definite integral. In the example figure, the grey area illustrates the probability that the NPV is positive, which in this example is quite small. If the variable is normally distributed, its PDF is called the Gaussian Curve. On the other hand, from the ECDF visualization can be read what is the probability that the variable receives a lower value than some certain value. From the example figure can be read that there is a 91 % probability that the NPV is below zero. Thus, PDF gives a better idea about the most probable values, but from ECDF is easy to quickly read certain probabilities. Using this kind of visualizations, however, requires that the probability distribution of the variable is known.

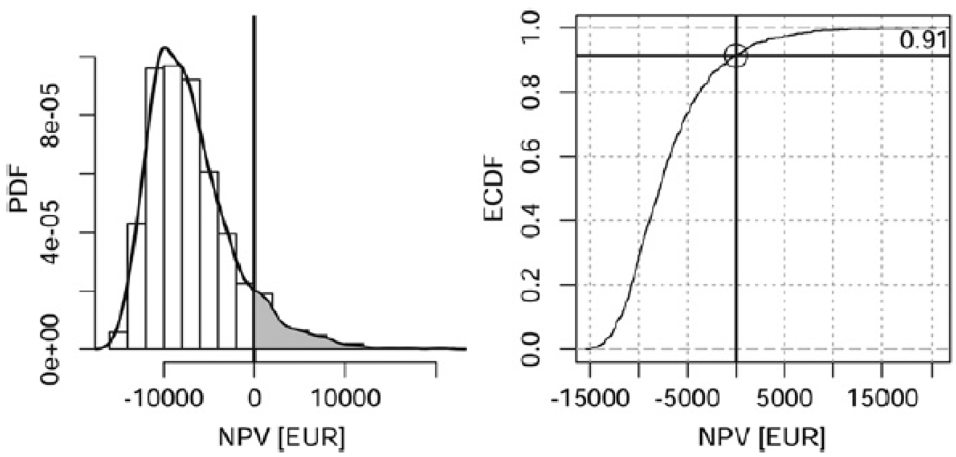


Figure 2.15. Examples of PDF and ECDF visualizations for net present value (NPV) [53]

An example of the histogram visualization is shown in Figure 2.16, which illustrates the uncertainty of the number of hours that exceed the summer set point temperature in a room. [50] In histograms, the range of values is divided into series of intervals and the amount of values in each interval is presented with bars. The data in the example figure is based on 500 simulations. With histogram, the dispersion of the results can easily be seen, as well as the most probable values. Additionally, it is possible to interpret if the distribution resembles some common distribution, such as the normal distribution.

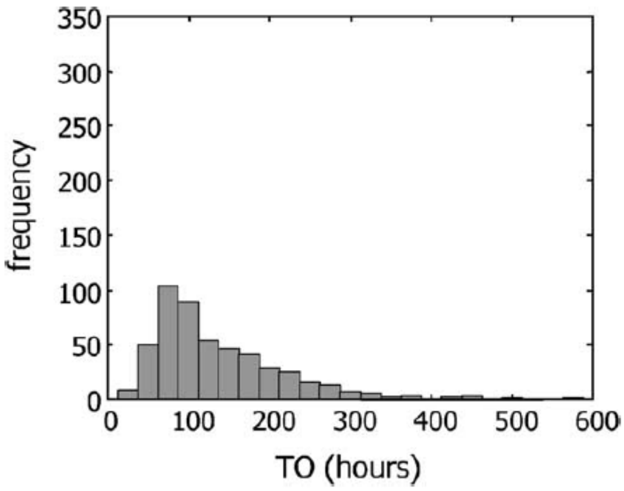


Figure 2.16. Example of uncertainty visualization with a histogram. [50]

PDF, ECDF and histogram are good for visualizing a single variable for one case. However, if it is required to visualize multiple series of data in the same graph, they might not be the best choice. This situation could be, for example, if the goal is to compare the uncertainties related to alternative building design solutions. In this case, the utilization of box plots for visualizing uncertainty might be more beneficial. An example visualization of the box plot is shown in Figure 2.17. In box plots, usually the median is used instead of the mean value, since it is more robust towards outliers (extreme values). The interquartile range (IQR) is used for describing the dispersion of the data. The IQR is the range that contains 50% of the ranked data around the median. Its lower limit is the lower quartile value (LQV) and the upper limit is the upper quartile value (UQV). Box plots are usually visualized with three elements: a box, “whiskers” and extreme values. The IQR is visualized as a box, and a horizontal line is drawn to represent the median. The whiskers show the range of the data, excluding the extreme values. The upper limit for the extreme values is calculated as the UQV + 1,5 · IQR, and the lower limit as the LQV – 1,5 · IQR. In the example visualization, the extreme values are marked with a plus sign. The box plot is a robust visualization method, since it does not require any statistical assumptions. In addition, it allows easy comparison of multiple series of results. [54]

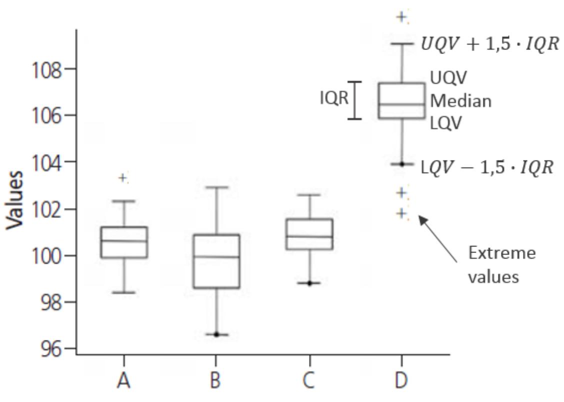


Figure 2.17. Example of uncertainty visualization with a box plot. [54]

3 New energy analysis process

The previous chapter reviewed the advanced methods (i.e. BIM, dynamic energy simulations, as well as sensitivity and uncertainty analyses) that are used in the new energy analysis process proposed in this thesis. In this chapter, the new process is introduced and the utilization of these advanced methods is described. The current nature of energy analysis is mostly a verifying tool to make sure that the design complies with the regulations as well as to produce energy consumption estimates or targets for the buildings. The aim of this process is to change the purpose of energy analysis to a tool that supports the design process itself already at the beginning of the project and produces alternative energy efficient retrofitting solutions. The utilization of BIM and dynamic energy simulation software that supports parametrization of inputs allows the integration of sensitivity and uncertainty analyses into the process in a user friendly manner.

First, Section 3.1 briefly presents the previous work that is utilized in the process and clarifies what new is developed in this thesis. The NewTREND project and thus also this work is based on three different modes of operation, which are described in Section 3.2. In this work, the Key Point Analysis tool is used for performing the sensitivity and uncertainty analyses, as well as the visualization of results. This tool is described in Section 3.3. The utilization of sensitivity and uncertainty analyses are described in their own sections, Section 3.4 and Section 3.5, respectively. Finally, section 3.6 provides an overview of the process with process flow charts and their explanations.

3.1 Previous work and developments made in this work

This thesis can be thought to be a continuation for two previous theses made for Granlund: Idman's thesis (2013) "Parametrization of energy simulation and development of energy-efficient building design, analysis and decision making process" [13] and Stjelja's thesis (2016) "Advanced energy analysis method for optimal building retrofit design" [17].

Idman's thesis [13] was made as a part of two different projects: Model Nova work package of the Finnish RYM PRE research program and EU funded ISES project. The aim of his thesis was to create and demonstrate a software environment, that allows the integrated utilization of multiple existing applications, thus increasing their use value. Therefore, he studied the general view of the energy analysis process, including the applied methods and their integration. As a result, an interactive decision making process was created in his thesis, which is presented in Figure 3.1. This process can be divided into three parts, which are parametrization, simulation and analyzing the results. Sensitivity analysis is utilized in the process for supporting the decision making process. Utilization of uncertainty analysis was also studied in his thesis, but it was left out of the process in order to make it more easily adopted. In addition, the thesis provided help in developing an interactive visualization environment in presenting the results. [13] Currently, this visualization environment is called the Key Point Analysis (KPA) tool. However, the process developed in Idman's thesis is intended only for designing new buildings. The process developed in this thesis, however, is for retrofit projects and thus has a different starting point and characteristics.

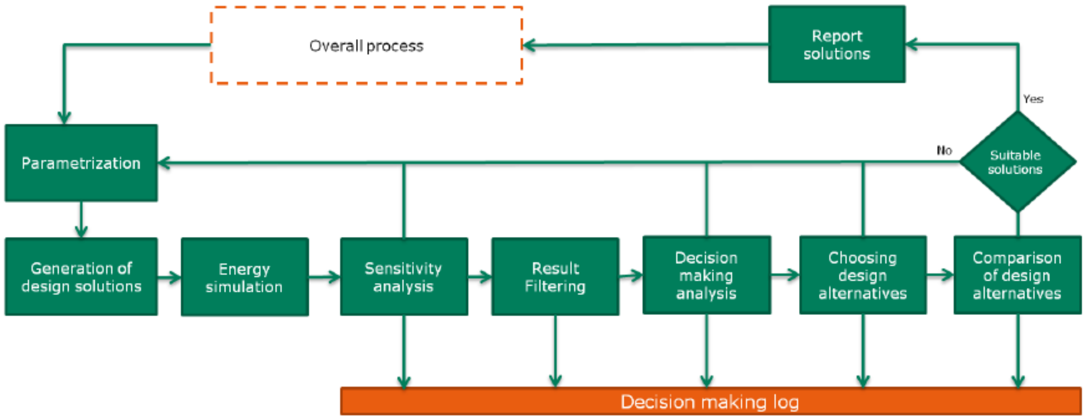


Figure 3.1. The process flow chart of the decision making process created in Idman's thesis. [13]

Stjelja [17] presented a new approach for energy analysis of existing buildings in his thesis. He introduced a BIM-based approach for energy analysis that could be utilized already from the very beginning of a retrofit project to guide the design process towards the most optimal retrofit alternative. At the beginning of the project, a less detailed BIM model can be used, as well as default values from regulations for the unknown parameters. As the project advances, the BIM model is complemented with more detailed information in order to obtain more reliable simulation results. Additionally, he presented a way of utilizing sensitivity analysis for guiding the challenging data collection task faced in retrofit projects. One of the main aspects in Stjelja's thesis was data collection, and his thesis includes a literature review of different methods for collecting geometry data and thermal properties from existing buildings. [17] This thesis aims to continue Stjelja's work by further defining, extending and testing the procedures and methods utilized in his thesis, and by creating a clear process description.

Since the process proposed in this thesis utilizes some elements from previous works, Figure 3.2 is presented in order to clarify which parts are from previous work and which parts have been developed in this thesis. This thesis utilizes the KPA tool, for which the sensitivity analysis method and visualization methods were implemented with the help of Idman's thesis [13]. The process utilizes similar procedures for the sensitivity analysis supporting data collection and for the utilization of BIM as was introduced in Stjelja's thesis [17]. The operational modes have been defined outside this thesis in the NewTREND project [55], but their utilization in the process has been defined in this thesis. The process flow and description introduced later in Section 3.6 have been developed in this thesis. In addition, the utilization of uncertainty analysis (Section 3.5) and the weighted sensitivity analysis visualization method (Section 3.4.3) have been developed in this work. The improved sensitivity and uncertainty analysis will be implemented in the KPA tool based on this work.

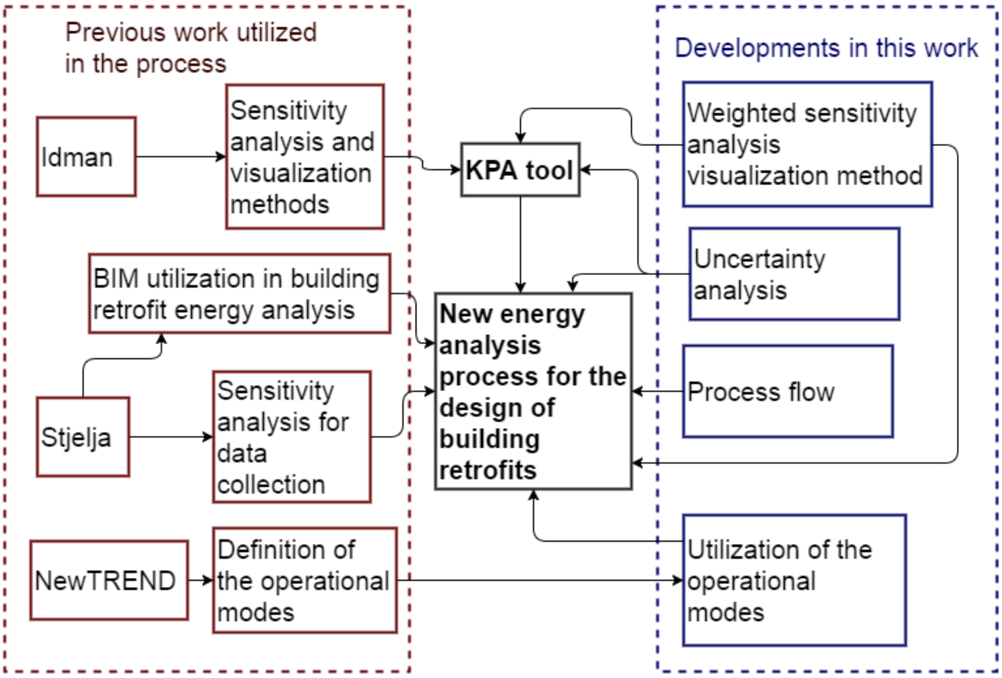


Figure 3.2. Previous work and developments made in this work.

3.2 The modes of operation

The task of data collection is much more challenging when retrofitting existing buildings than when designing new buildings. It is often the case that the required information about the building is confined inside the structures, or that the available drawings and reports do not give an accurate description of the up-to-date state of the building. This causes determining all the needed information accurately to be expensive and time consuming. In order to overcome this problem, three different modes of operation with different data requirements are used in the NewTREND project [55], which will also be used in this thesis. The modes are named as basic mode, advanced mode and premium mode. Each mode produces different outputs depending on the quantity and accuracy of the provided information. [55]

As a starting point, all three modes of operation require a BIM model of the building or neighborhood, which is complemented with semantic data. The modes differ from each other in the quantity and level of accuracy of the geometric and semantic data. The basic mode is the mode with the lowest data requirements, and therefore the generated outputs are the most limited. The advanced and premium modes have higher data requirements, allowing more output options. The main difference between the advanced and the premium mode is the source of the data, as premium mode uses measured as-is values, and advanced mode relies on other sources such as existing plans and occupant questionnaires. In the framework of this thesis, only basic and advanced modes are included. Nevertheless, in order to give a broader overall picture, premium mode is also described. Figure 3.3 illustrates the inputs and outputs of each mode. However, the exact way of how these modes will function in the NewTREND methodology is still going to be further refined later in the project. [55] These three modes of operation are described in more detail in Sections 3.2.1 - 3.2.3. The main differences in the data requirements of the modes are summarized in Table 3.1.

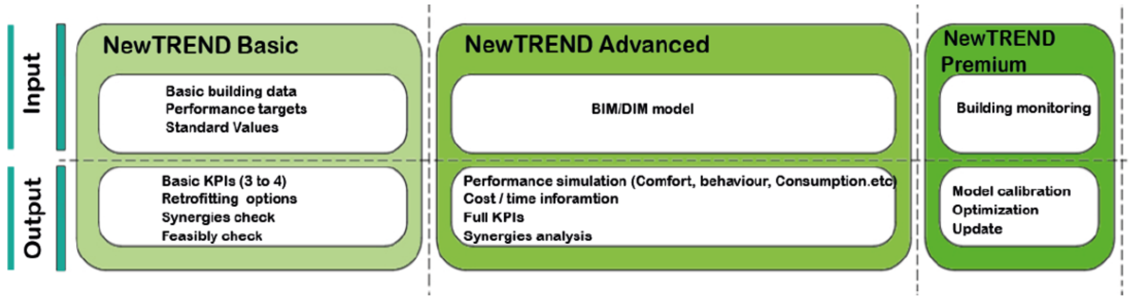


Figure 3.3. Inputs and outputs of the three modes of operation. [55] The process developed in this thesis utilizes only the basic and advanced modes for the design of building retrofits. The premium mode could be used after the retrofitting e.g. for model calibration and optimization.

Table 3.1. Summary of data requirements for the three modes of operation.

Mode	Reliability of information	Geometry model	Main source of information
Basic	LOD200 (AIA specification)	CityGML LOD2, with approximate area of windows	Default values from regulations and statistics
Advanced	LOD 300 (AIA specification)	CityGML LOD4	Plans, reports, user and owner questionnaires etc.
Premium	LOD 500 (AIA specification)	CityGML LOD4	Measured values

3.2.1 Basic mode

Older existing buildings rarely have BIM models available, and the process of creating a full BIM model of an existing building is often very time consuming and resource intensive. Therefore, basic mode is used as a link between the gap of full BIM model and traditional two dimensional drawings. This mode relies mostly on default values, while utilizing results from previous research projects and other easily accessible information sources. Thus, basic mode allows easily generating rough results about any building in the neighborhood. However, the accuracy of the results cannot fully be depended upon, since the mode heavily depends upon inferred default values instead of actual real life data. Moreover, the outputs are limited to energy and life cycle cost related outputs, ruling out user comfort related outputs. [55] In the process proposed in this thesis, the basic mode is used for assessing the energy saving potential of the buildings and for preliminary retrofit design.

All three modes of operation, including the basic mode, require a BIM model. Section 2.1.4 discussed the specifications for levels of detail and levels of development of BIM models. The data requirements used in the NewTREND modes of operation combine the level of development specification by AIA and the level of detail specified by CityGML. In the basic mode, the building geometry has to satisfy CityGML LOD2 level and the related building information reliability has to equal to a BIM model of AIA LOD200 [55]. As described in Table 2.1 (section 2.1.4), LOD200 means that: "*any information derived from LOD 200 elements must be considered approximate* [34]." CityGML LOD2 would mean that the building is modeled without windows [38], which would cause big errors in the energy simulations. Therefore, in the basic mode of this work, the windows are modeled as an approximation of the percentage of window area per exterior wall area. In RIUSKA, there is an automatic tool that can create the windows. Individual rooms are not modeled at this mode, but if positions and properties of different thermal or user zones are known, they should be modeled. To get any sensible results, non-geometry related data is also needed in each mode of operation, including information about the structures, glazing and technical systems. For parameters that cannot be determined easily, default values from regulations or building statistics are used. In the basic mode, the importance of unknown parameters should be assessed with sensitivity analysis.

3.2.2 Advanced mode

The advanced mode is more demanding in data requirements than the basic mode. This mode requires that the building has a well detailed BIM model, thus allowing the performing of accurate energy and indoor comfort analysis on a single room level. In contrast to the basic mode, data acquired from different sources, such as drawings and documents, is used as much as possible instead of default values. [55] In the process proposed in this thesis, the advanced mode is used for supporting the decision making in the retrofit design by comparing various retrofit alternatives.

In the advanced mode, the building geometry has to satisfy CityGML LOD4 level and the building information reliability has to equal to a BIM model of AIA's LOD300 [55]. CityGML LOD4 requires that the building model includes accurate exterior walls, windows and roofs as well as interior features, such as interior walls, staircases and furniture [38]. However, in this thesis, of interior features only interior walls are modeled so that rooms can be defined, disregarding less relevant interior features. Windows are, however, modeled accurately in this mode. The BIMforum interpretation for AIA's LOD300 is: "*The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs* [34]." This would require that default values are no longer used. Nevertheless, if some parameter has been proven to have little influence based on sensitivity analysis, and it would require noticeable time and effort to acquire the information, then default value could be used.

3.2.3 Premium mode

The premium mode has the highest data requirements, as it requires a highly detailed BIM model of the building that corresponds to the actual state of the building. As can be seen from Figure 3.3, the premium mode is intended to be used once the retrofitting is complete for facility management purposes, such as optimization of the technical systems. The premium mode BIM model is also a convenient place to store all the building related information in one place for future needs. [55] Since the energy analysis process developed in this work covers only the pre-construction phase of the project, the premium mode is not utilized in this work.

In the premium mode, the building geometry requirements are the same as for the advanced mode, but the related building information reliability has to be equal to AIA's LOD500, which means that the information has been verified in the field. In practice, this means that the premium mode operates mostly with real-time measurements and actual data from building automation system, which is the main difference in contrast to the advanced mode. [55]

3.3 The Key Point Analysis tool

The Key Point Analysis (KPA) tool is used in the piloting of the new process. It is a web-based visualization environment developed by Granlund Oy in collaboration with RYM PRE Model Nova and ISES-projects. The purpose of the KPA tool is to allow analyzing increased number of design alternatives in order to find the optimal solution. This tool has been developed to function with the RIUSKA simulation tool, but can also work with other software, provided that the input file is modified into the same form. In RIUSKA, the results of the parametrized simulation are saved into a comma-separated values (CSV) file, which is then uploaded into the KPA tool for analyzing. The tool consists of three sections, namely simulation synthesis, key performance indicator (KPI) analysis and decision value analysis. Decision value analysis, however, is not used in this thesis, and thus it is not presented here. KPIs are values that indicate how well the building performs from different points of view. For example, heating energy consumption and life cycle costs (LCC) are KPIs.

3.3.1 Simulation synthesis

This tool automatically performs sensitivity analysis for the uploaded CSV-file and visualizes the results with bar charts. The tool uses regression method with standardized regression coefficients (SRC) for sensitivity analysis. Reasons for why this method has been chosen are explained later in Section 3.4.1. The sensitivities of all KPIs can be seen at once (Figure 3.4) and for each KPI separately (Figure 3.5). In these sensitivity analysis visualizations, the numerical values of the y-axis are not shown, since the visualization is only intended to compare the relative influence of the different parameters. In the piloting part of this work, however, the sensitivity analysis results are shown with the numerical y-axis values. Investment costs and LCC calculation have not yet been implemented in the official version of RIUSKA, but it is currently in the making. The CSV-file automatically created by RIUSKA currently contains the following KPIs:

- total energy need
- heating/cooling energy need
- electrical energy need
- purchased energy cost
- purchased energy CO_2
- primary energy (E-value)
- comfort index
- building envelope heat loss
- heating/cooling space maximum power
- heating/cooling air conditioning maximum power
- heating/cooling total maximum power

The comfort index used in RIUSKA describes the average indoor temperature constancy in the building throughout the year. For each room, RIUSKA calculates the indoor temperature constancy by dividing the time inside the desired range (e.g. 21 – 25 °C) by the total building usage time. This quotient is then multiplied with 100 % in order to get a percentage. The comfort index is then calculated as an average of these constancies, weighted by the floor areas of the rooms. Thus, the best possible value for the comfort index is 100 %, which would mean that temperatures in all the rooms are between desired minimum and maximum values during all times.

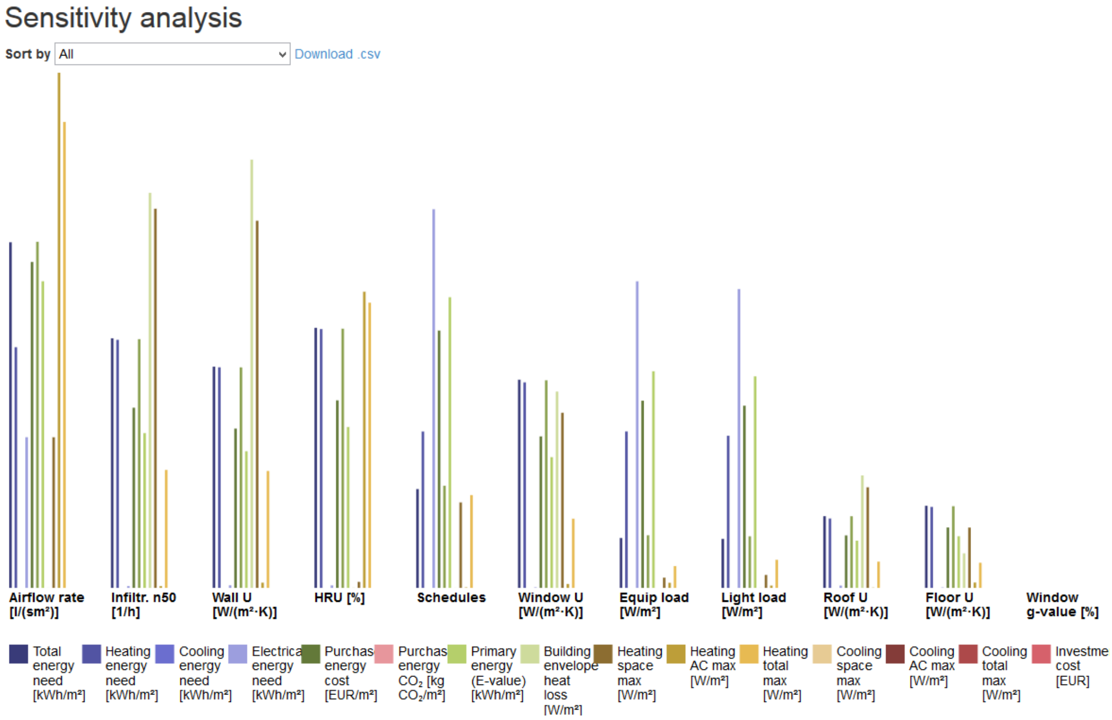


Figure 3.4. Visualization of all KPI sensitivities at once.

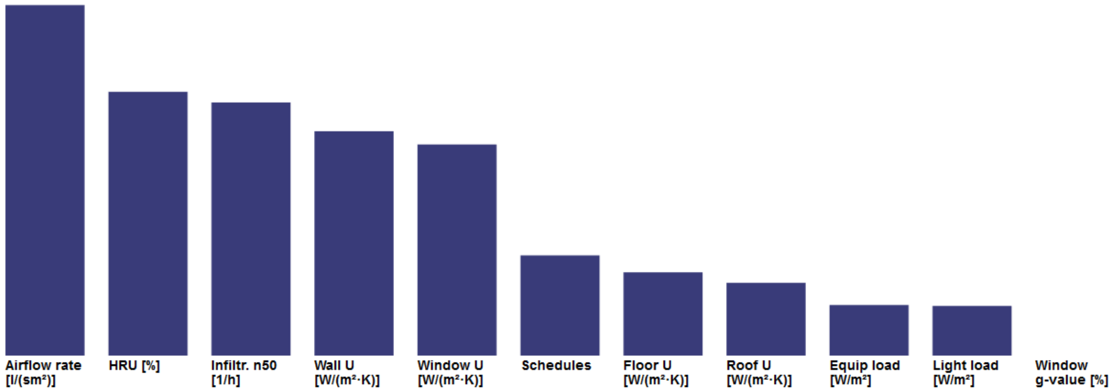


Figure 3.5. Sensitivity analysis visualization for one individual KPI (total energy need).

The tool also has a "requirement setup" section, where it is possible to filter, group and weight all the KPIs (Figure 3.6). For example, the user can filter the results by setting a requirement that the total energy need has to be smaller than 200 kWh/m^2, causing the cases not meeting this target to be faded out in the KPI analysis. Additionally, the user can create a KPI group named "energy need" that includes heating, cooling, electricity and total energy need. This group can then be given any weighting factor, which is taken into account in the decision value analysis. Currently, the weighting does not affect the sensitivity analysis. Nevertheless, in the Section 3.4.3 of this work it is discussed whether it would be feasible to include the weighting factors also in the sensitivity analysis in order to present only one combined and weighted sensitivity.

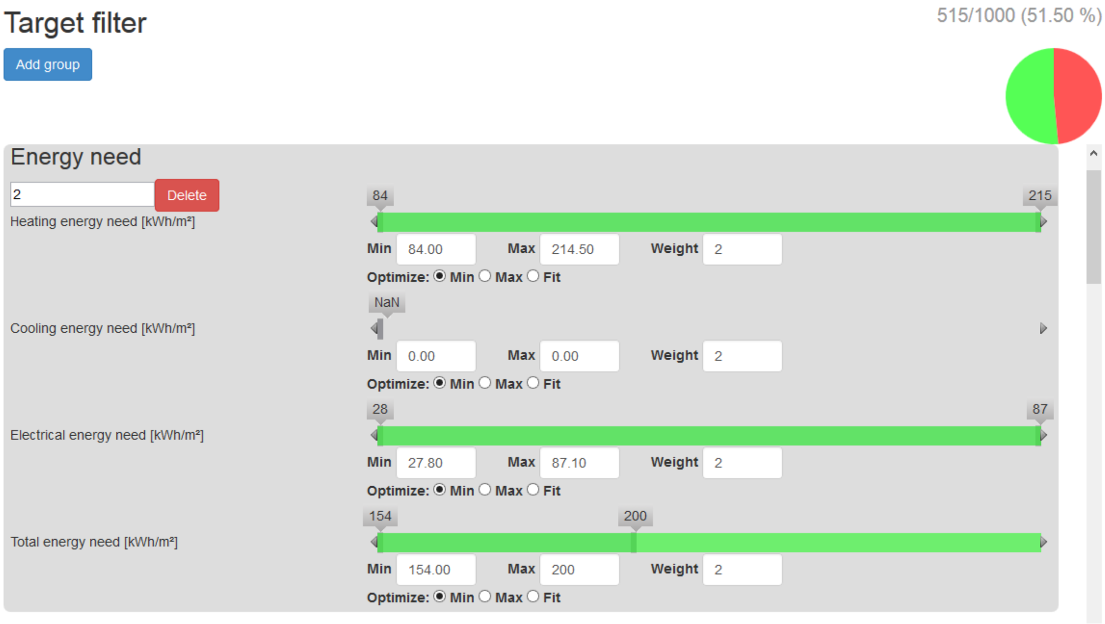


Figure 3.6. Target filter feature for filtering, grouping and weighting the KPIs.

3.3.2 KPI analysis

The decision making in building design is always a multi-objective problem, which means finding the best possible design alternative between multiple conflicting objectives. In general, the goal is to design buildings that consume the least possible energy while maintaining costs as low as possible. This is problematic, since better energy efficiency almost always comes with higher investment costs. Different kinds of informative visualizations are needed in order to support the decision making. The KPI analysis section of the tool supports four different visualization methods: scatter diagram, hyper radial visualization, parallel coordinate plot (PCP) and radar chart. It is possible to highlight one individual simulation case in each visualization simultaneously, which allows easy examination of a single case from different points of view. In this thesis, only scatter plot and PCP are used.

Scatter diagram (Figure 3.7) presents the results of all the simulated cases with respect to the chosen KPIs. The user can choose which KPI to present on the x and y-axis. In addition, a third KPI can be visualized with a color code. In the example visualization below, cooling and heating energy needs are chosen for the axes, and total energy need is visualized with color code. Each circle represents one simulation case, and by bringing the cursor over any circle, the input parameters and KPIs of that case are shown. Scatter diagram can be used to find the Pareto frontier, which consists of the non-dominant cases, i.e. the cases that are equally good in terms of the KPIs on the axes. This is especially beneficial with costs on the other axis and some energy related KPI on the other axis. Scatter diagram does not directly give information about the input parameters of the cases. Thus, it cannot be used for finding correlations between KPIs and input parameters.

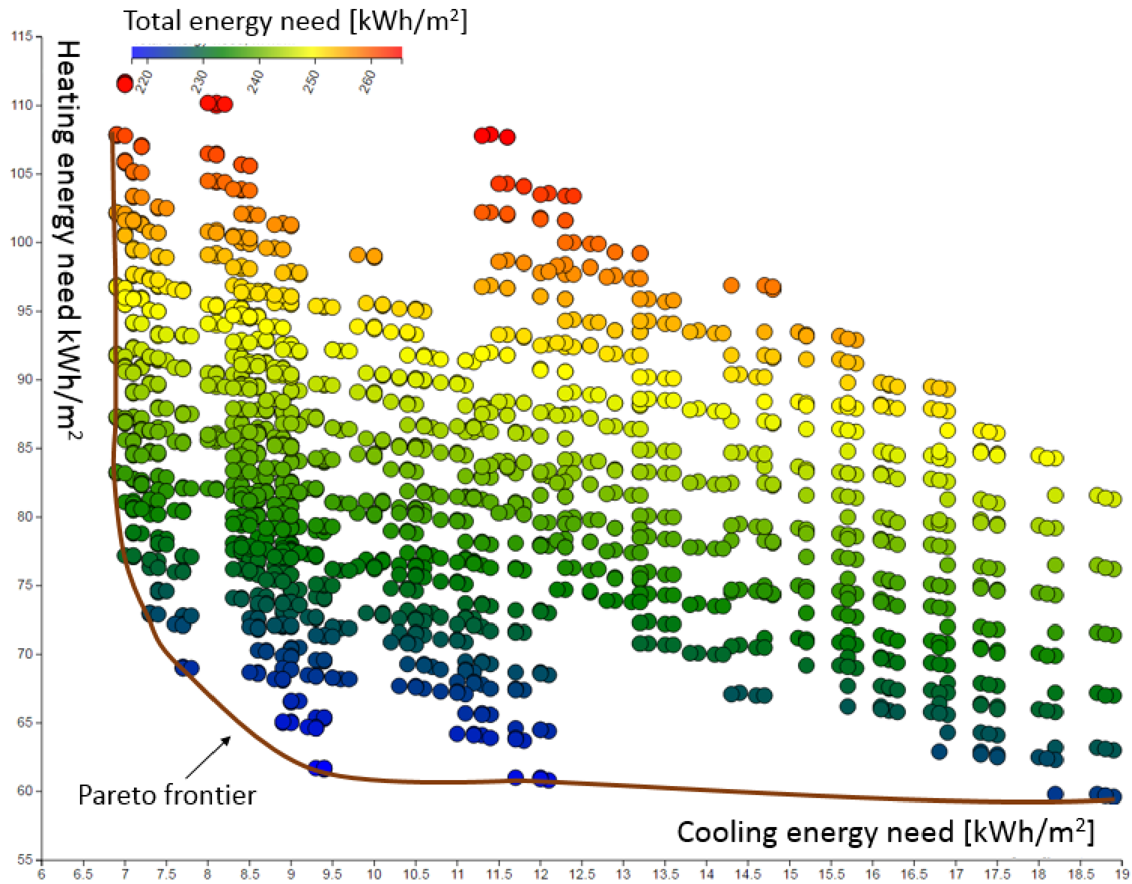


Figure 3.7. Example of a scatter diagram created with the KPA tool, with added Pareto frontier.

An example of the PCP visualization is illustrated in Figure 3.8. PCP is a simple way to visualize multidimensional data in two dimensions. The user can choose which input parameters and KPIs are presented in the plot. The number of parameters and KPIs is not restricted, but too many of them can make the plot difficult to interpret. Each of these are visualized on a vertical axis with own corresponding units and value ranges. Each simulation case is represented with a polyline that connects the values of each individual case. The lines are color coded based on the values of the KPI positioned on the left-hand side in order to make the plot easier to interpret. Additionally, it is possible to filter the simulation cases by narrowing the ranges of KPIs and input parameters. The filtering feature is demonstrated later in this work in Section 4.2.4.3. In the example visualization below, all the cases go through the same knot in cooling energy, because in this example the building does not have cooling. Knots are formed also in the vertical axes of the input parameters, since discrete values are used for the inputs. In this example visualization, window can have only value 3,3 W/m^{2}K or 2,78 W/m^{2}K, causing all the lines to go through either of these points.

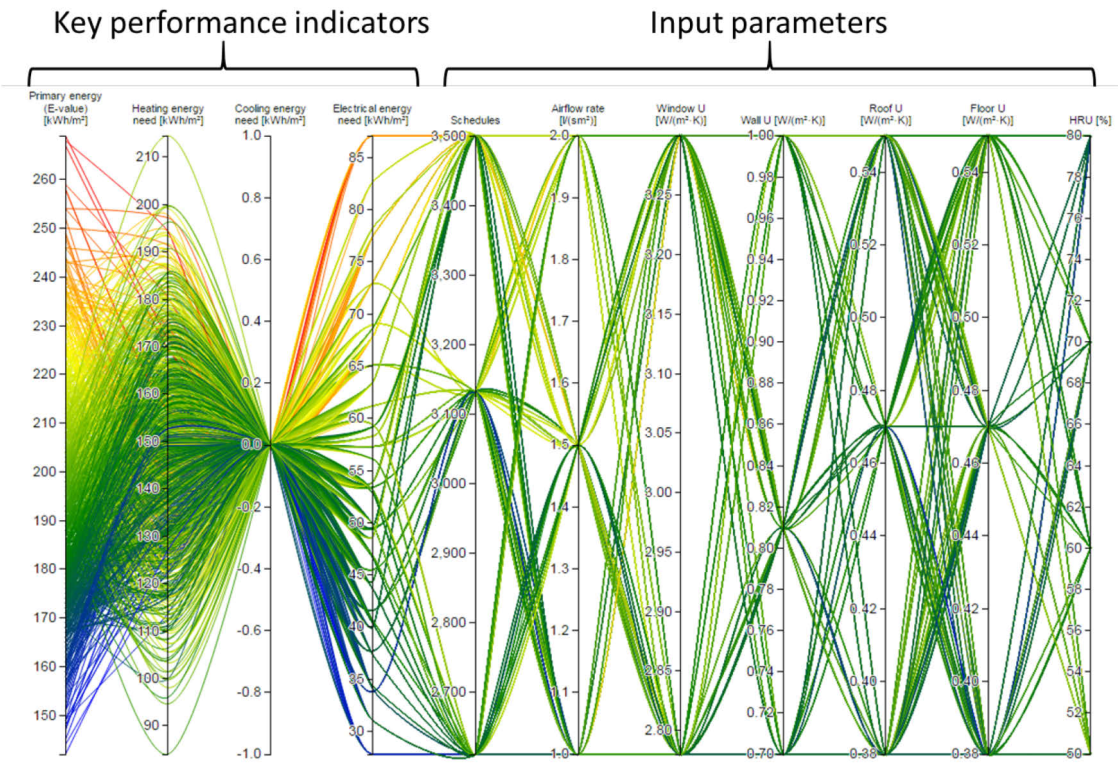


Figure 3.8. Example of a parallel coordinate plot created with the KPA tool.

3.4 Sensitivity analysis

In this section, the utilization of sensitivity analysis in the process will be described. First, the reasons for choosing the regression method with SRCs are presented. Then, the procedure of utilizing sensitivity analysis to orient the data collection is described in more detail. In addition, the new weighted visualization method for sensitivity analysis is introduced.

3.4.1 Choosing of the method

The sensitivity analysis method used in this work is the one that was previously implemented in the KPA tool. The choosing of the method for the tool was based on Idman's [13] thesis. Idman concluded in his work, that based on his literature review, the most used sensitivity analysis methods in building energy simulations are the local influence coefficient (IC) and methods based on regression, such as standardized regression coefficients (SRC), standardized rank regression coefficients (SRRC) and partial rank correlation coefficients (PRCC). More information about these methods can be found for example in [16]. The chosen method was required to be able to produce quantitative and reliable results with a relatively small amount of simulations. Additionally, the results should represent the relative importance between different parameters.

Idman [13] tested four different sensitivity analysis methods in his thesis: local influence coefficient (IC), as well as regression methods SRC, SRCC and PRCC. Idman concluded that local influence coefficient method did not produce quantitative results that would represent the whole solution group. On the other hand, it was shown that SRC and SRCC regression methods produced reliable results with a relatively small amount of simulations. However, since SRCC is performed on assigned ranks instead of real values, they do not produce quantitative results. In conclusion, regression method with SRCs was chosen to be used in the KPA tool. [13]

3.4.2 Sensitivity analysis for supporting data collection

It is very common that in retrofit projects at least some of the needed information about the building is missing. Acquiring all of the missing information through site visits and measurements can be time consuming and expensive, thus it would be sensible to investigate which parameters are the most important to be determined accurately. Stjelja [17] showed in his thesis how sensitivity analysis could be used to determine which parameters have the most influence for each KPI in order to guide the data collection.

The first, and also the most important step in sensitivity analysis is to define the possible ranges for the input parameters that reflect the real building. This should be done with careful consideration, taking the construction year and other known information into account. Values from regulations of different years can be used as a starting point for the ranges, but the best way would be to use the knowledge of seasoned experts, if possible. Also, building stock statistics or knowledge from other projects could be used, if they exist and are available. [17] For example, in the IEE project TABULA [56], typologies for residential buildings in thirteen European countries were determined, where the buildings are grouped according to size, age and further parameters. In that project, also a web tool was created, which includes a set of exemplary buildings representing the building types. Unfortunately, this database cannot be used in this work, since the TABULA project only included residential buildings. Also, if standard deviations and means for the input parameters were known, then normal distributions could be used in determining the variations. However, these are difficult to estimate case specifically, and thus a simple uniform distribution is used for each parameter in this work.

Usually the number of possible input parameter combinations can be very high, and thus it is advisable to simulate a random sample instead of simulating every possible case [17]. For example, if ten parameters each had five possible values, then the number of combinations would be $5^{10} = 9765625$. In addition to simple random sampling, there are other more advanced methods, such as stratified and Latin Hypercube sampling. Nevertheless, Macdonald [57] showed in his paper that simple random sampling, stratified sampling and Latin Hypercube sampling do not seem to produce significantly different results, and suggested that for typical building simulation applications about 100 simulations and simple random sampling should be used. Therefore, simple random sampling is used in this work as well. However, since the number of parametrized inputs is quite high in this work, 1000 simulations is used in order to ensure more reliable results.

After the random sample has been generated, it is simulated and the sensitivity analysis is performed for each KPI [17]. In this work, the sensitivity analysis and the visualization of results are done with the KPA tool. The sensitivity analysis results can then be used to decide which parameters need to be determined more accurately and for which default values could be used [17]. A demonstration of how this procedure works is given later in this work in Section 4.2.4.

3.4.3 New weighted visualization method

Currently, it is possible to show only sensitivities of separate KPIs (Figure 3.5) or all KPIs (Figure 3.4) at the same time in the KPA tool. The visualization with all the KPIs is not very informative, because of the large number of thin bars. Thus, it can be difficult to get a good overall view of the sensitivities. In this work, a new weighted visualization method for sensitivity analysis is introduced and demonstrated in order to solve this problem.

The idea is to divide the KPIs into a few groups, for which the user can give specific weighting factors in the "Requirement setup" section of the KPA tool. One suggestion for the grouping is given in Table 3.2. This could be a default grouping, which could be changed by the user if necessary. The weighting is done with percentages. For example, the user could input 40 % for costs, 20 % for energy, 20 % for comfort, 10 % for emissions and 10 % for sizing. These weighting factors are then taken into account in visualizing only one combined sensitivity bar chart, which takes all the KPIs into account. This is done by simply calculating the weighted averages of all the SRC values for each parameter.

This kind of visualization method makes it possible to show only one sensitivity bar chart, which includes all the KPIs and takes the preferences of the user into account. By dividing the KPIs into groups, it is easier and faster to determine these weighting percentages. This visualization method, however, is not useful in the sensitivity analysis for data collection, because at that phase it is only beneficial to assess the sensitivity of energy consumptions. Instead, when simulating different retrofit design alternatives, this could be used to assess which are the most important elements to retrofit based on the user's preferences. This new visualization method will be demonstrated later in Section 4.3.3.2, as a part of the process piloting.

Table 3.2. Suggestion for dividing the KPIs into groups.

Group name	Key performance indicator
Costs	LCC [€]
	Investment cost [€]
	Purchased energy cost [€/m²]
Energy	Total energy need [kWh/m²]
	Heating energy need [kWh/m²]
	Cooling energy need [kWh/m²]
	Electrical energy need [kWh/m²]
	Primary energy (E-value) [kWh/m²]
Comfort	Comfort index [%]
Emissions	Purchased energy CO_2 [kg CO_2/m²]
Sizing	Building envelope heat loss [W/m²]
	Heating space max [W/m²]
	Heating AC max [W/m²]
	Heating total max [W/m²]
	Cooling space max [W/m²]
	Cooling AC max [W/m²]
	Cooling total max [W/m²]

3.5 Uncertainty analysis

Currently, uncertainty analysis is not supported in the KPA tool. Since it would be important to take the uncertainties into account in the decision making, uncertainty analysis is included in the process and will be implemented in the KPA tool in the framework of this thesis.

3.5.1 Implementation in the KPA tool

For the implementation of uncertainty analysis in the KPA tool, some requirements were set. The uncertainty analysis setup should be easy for the user, while providing informative visualization. The visualization should also allow easy comparison of various retrofitting alternatives. In addition, it should be possible to simulate and analyze certain and uncertain parameters at the same time. In other words, the KPA tool needs to have a function to separate design (certain) and scenario (uncertain) parameters from each other.

In order to simulate and analyze certain and uncertain parameters at the same time, it was decided that the user can divide the simulation input parameters into design parameters and uncertain scenario parameters. Design parameters are considered to be certain, and they define the design alternatives. The other parameters are considered to be uncertain, which cause the uncertainties in the results. In Figure 3.9 is presented a simple version of a CSV-file which is uploaded into the KPA tool. In this case, window area and the U-values of walls, roofs and floors are chosen as the defining design parameters, while internal load schedules are uncertain scenario parameters. The tool then groups all cases that have the same design parameters into the same group, in this example to alternative 1 and alternative 2. Thus, the variation in the output caused by the uncertain parameters can be seen in the KPI column. This allows the uncertainties to be simulated in the same simulation round as the design alternatives.

	Design parameters				Uncertain parameters			KPIs
	Wall U...	Roof U...	Floor U...	Window mÂ...	People load sc...	Equip load sch...	Light load sch...	kpi_Total ener...
Alt. 1	0.12	0.13	0.13	15	1377	1566	1377	101.9
	0.12	0.13	0.13	15	1377	1377	2628	110.7
	0.12	0.13	0.13	15	1377	1566	1566	102.8
	0.12	0.13	0.13	15	1566	1377	1377	99.5
	0.12	0.13	0.13	15	1377	1566	2628	111.2
	0.12	0.13	0.13	15	1566	1566	1566	105.3
Alt. 2	0.17	0.19	0.16	20	1566	1566	2628	114.8
	0.17	0.19	0.16	20	1566	1377	1377	104.7
	0.17	0.19	0.16	20	1566	1377	1566	105.6
	0.17	0.19	0.16	20	1566	1377	2628	114.2
	0.17	0.19	0.16	20	1566	1377	2628	133.6
	0.17	0.19	0.16	20	1566	1377	1566	127.2

Figure 3.9. Division of parameters into design parameters and uncertain parameters.

There are multiple possibilities for the visualization of the uncertainty, such as histograms, different kinds of box plot, as well as the PDF and ECDF. However, at this stage only a simple scatter plot for the visualization of minimum, maximum and average values was implemented. An example of this visualization is shown in Figure 3.10. The different design alternatives are lined up in the x-axis with ID-numbers, and the chosen KPI is on the y-axis. Each red dot represents one simulation case. The user can freely change the design parameters that define the alternatives and the KPI shown in the y-axis. This visualization method was easy to implement, easy to understand and it allows easy comparison of various design alternatives simultaneously. However, it does not provide much information about the dispersion of the cases. Nevertheless, uncertainty analysis in the KPA tool will be tested with this simple visualization first, and more advanced methods are considered later, if necessary.

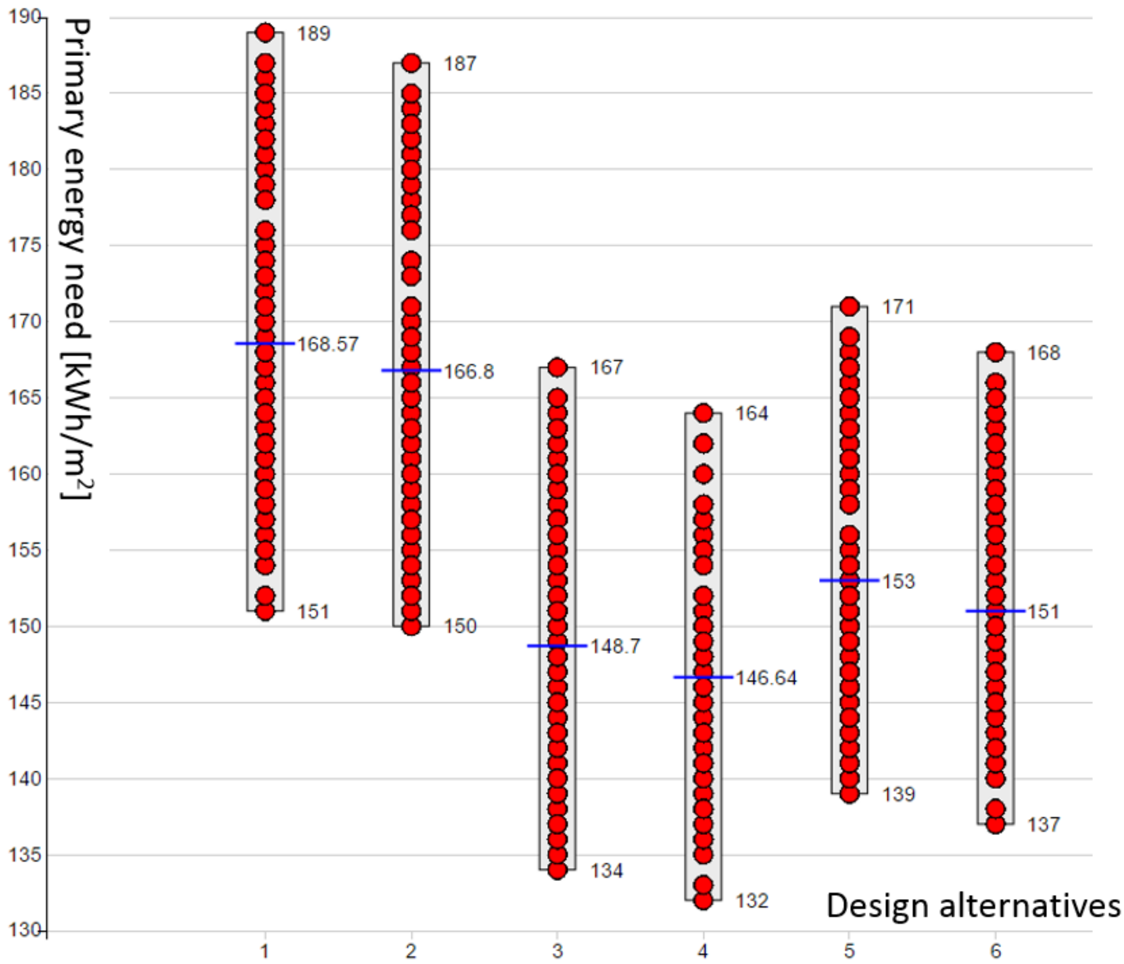


Figure 3.10. Visualization of the uncertainties in the KPA tool. This example figure illustrates the uncertainty of primary energy need for six different retrofit design alternatives.

3.5.2 Utilization in the process

Two different options were considered for implementing uncertainty analysis in the process. The first option is to include the uncertain parameters already in the first retrofit alternative simulations. This would make the process faster and simpler, since only one simulation round would give KPI results, as well as uncertainty and sensitivity analysis results. However, this would increase the number of combinations dramatically. For example, if there are 1000 possible retrofit alternatives, and 1000 possible uncertainty scenarios, the total number of combinations would be one million. A group this large would need much larger random sample in order to represent all alternatives sufficiently. Moreover, with the random sample there would also be a risk that the uncertain scenarios would not distribute evenly among the different alternatives. For example, one design alternative could get the worst case scenario from the random sampling, while some other alternative does not get it, which would make the other alternative look better. Also, simulating retrofit alternatives and uncertainties at the same time would make the sensitivity analysis results difficult to interpret. It would be better to analyze the sensitivity to design parameters and to uncertain parameters separately.

The second option is to first simulate a larger group of retrofit design alternatives without uncertainty analysis. After analyzing the results, a smaller group of promising alternatives is chosen from the large group, for which the uncertainty analysis is performed with another simulation round. This would solve the problem of too large total number of combinations for one simulation round. Additionally, this allows more uncertain scenarios to be simulated with the same computational time, since the uncertainty simulation is done only for a smaller group. It might also be feasible to simulate all the uncertain scenarios in the second simulation round, because some of the uncertain parameters do not require energy calculation, making the calculation much faster. As a drawback, this option causes a bit more work for the user, since another simulation round is required. Furthermore, uncertainties are only analyzed for the chosen small group in this option.

Both options were tested with test simulation rounds. The first option proved to be hard to interpret in the KPA tool visualization, since there was not yet any way of seeing which uncertain cases belong to which design alternative in the scatter plot. At this point, the grouping of design parameters and uncertain parameters only functioned for the uncertainty visualization (Figure 3.10). Thus, it was difficult to determine which design alternatives seemed promising, since the scatter plot was mixed with the different uncertain scenarios. The second option did not have these problems with the visualization. Additionally, it was assumed that it is enough to evaluate the uncertainties of only the most promising design alternatives. Therefore, the second option was chosen as the way of utilizing uncertainty analysis in the process.

3.6 Process flow and description

The proposed process for energy analysis of neighborhood-scale retrofit projects is presented in the following two sections, divided into the basic and advanced modes. This process flow has been fully developed in this thesis, while utilizing parts from previous work, as described in Section 3.1. The two operational modes act as phases in the process. Building retrofit projects are started in the basic mode, which could be utilized in the conceptual design phase. Based on the results obtained from the basic mode energy analysis, it is decided whether further energy analysis is needed or not. If retrofitting the building or multiple buildings appears to be feasible and more accurate simulations are required, the project should move forward to the advanced mode. The advanced mode could be utilized in the schematic design and design development phases.

In this work, only the pre-construction part of energy analyses is considered. The operations made in both modes are illustrated in separate process flow charts (Figure 3.11 and Figure 3.12), and described with more detail in the text. In these figures, abbreviation “SA” is used for sensitivity analysis and “UA” for uncertainty analysis. Here, the process is described only in a rather general way, and thus it might be hard to assimilate. A clearer view of the process should be formed after reading Chapter 4, in which the process is tested.

3.6.1 Basic mode

In the basic mode, the process is divided into the following three steps (Figure 3.11):

1. Assess the energy saving potential of the buildings
2. Define the current state of the building that is chosen to be retrofitted
3. Feasibility check

The purpose of **the first step** is to roughly estimate the energy saving potential and profitability of retrofitting each building in the neighborhood. Based on these results, it can be decided which of the buildings will be retrofitted. The process begins by creating basic level BIM models of all the neighborhood buildings for building energy simulation purposes. If architectural drawings of the buildings are available, it is relatively fast to create these simple models, since they are modeled without windows and rooms. However, if the drawings cannot be acquired at this point, the basic mode BIM models can be created with the help of any free online mapping service, such as Google maps, OpenStreetMaps or Here Maps. This kind of procedure was described and tested in Stjelja's [17] thesis. Once the BIM models have been created for the buildings, their current state energy use is analyzed with energy simulations. At this point, most of the input parameters are still unknown. Therefore, default values from regulations or building stock statistics are used, taking into account the building type and construction year. However, in order to get any sensible results, the types of HVAC systems, used energy sources, building types and construction years should be known. Next, preliminary retrofit solutions are determined and simulated. At this point, too much time should not be used for determining what retrofit solutions are simulated, since the aim is simply to estimate and compare the energy saving potentials of the buildings. Also, a suggestive life cycle cost analysis (LCCA) is performed for the simulated retrofit solutions. Based on the results, it is decided which building or buildings are going to be retrofitted. To simplify, let us assume that only one building is chosen to be retrofitted.

The aim of **the second step** is to define the current state of the chosen building in order to perform more accurate energy and LCC analysis. Most likely there is a lot of missing data at this point. Therefore, sensitivity analysis is performed to support data collection, as described previously in Section 3.4.2. Parameters that show high sensitivity for important KPIs should then be obtained from whichever source is the most appropriate. For parameters that show low sensitivity, default values can be used. At this point it would also be beneficial to obtain historical energy consumption data for the building. Usually utility bills are the easiest way of acquiring this information. This information can then be used to filter the simulated cases to find the case that best represents the actual building and its real energy consumptions. It is also possible that when gathering information about the input parameters, the range of possible values is only narrowed down instead of obtaining one absolute value. In this case, filtering the already simulated cases can be particularly beneficial. Using this kind of procedure allows creating a good representation of the actual building only by simulations with roughly estimated values and brief additional data collection. At this phase the outputs (results) of the energy simulation model are not yet very accurate but can give good guidelines for the project.

With the information obtained in the second step, a bit more realistic energy simulation model of the building's current state is created. Thus, the economic feasibility of the retrofitting should be assessed again. This is conducted in **the third step**. The same retrofit solutions that were used in the first step should be simulated in this step as well in order to assess if the situation has changed in consequence of the acquired information. If retrofitting the building still seems feasible based on the results of this step, the project should move forward to the advanced mode.

Any final decisions about the retrofitting of the building is not yet done in the basic mode, since the aim is only to choose the building to be retrofitted as well as to roughly estimate the building's current state and the feasibility of retrofitting. Also, the results cannot yet be fully relied upon, since simple BIM models and many default values or values from statistics are used. Thus, it is not yet sensible to assess the uncertainties at this point. Instead, uncertainty analysis is implemented in the advanced mode, which is described in the next section.

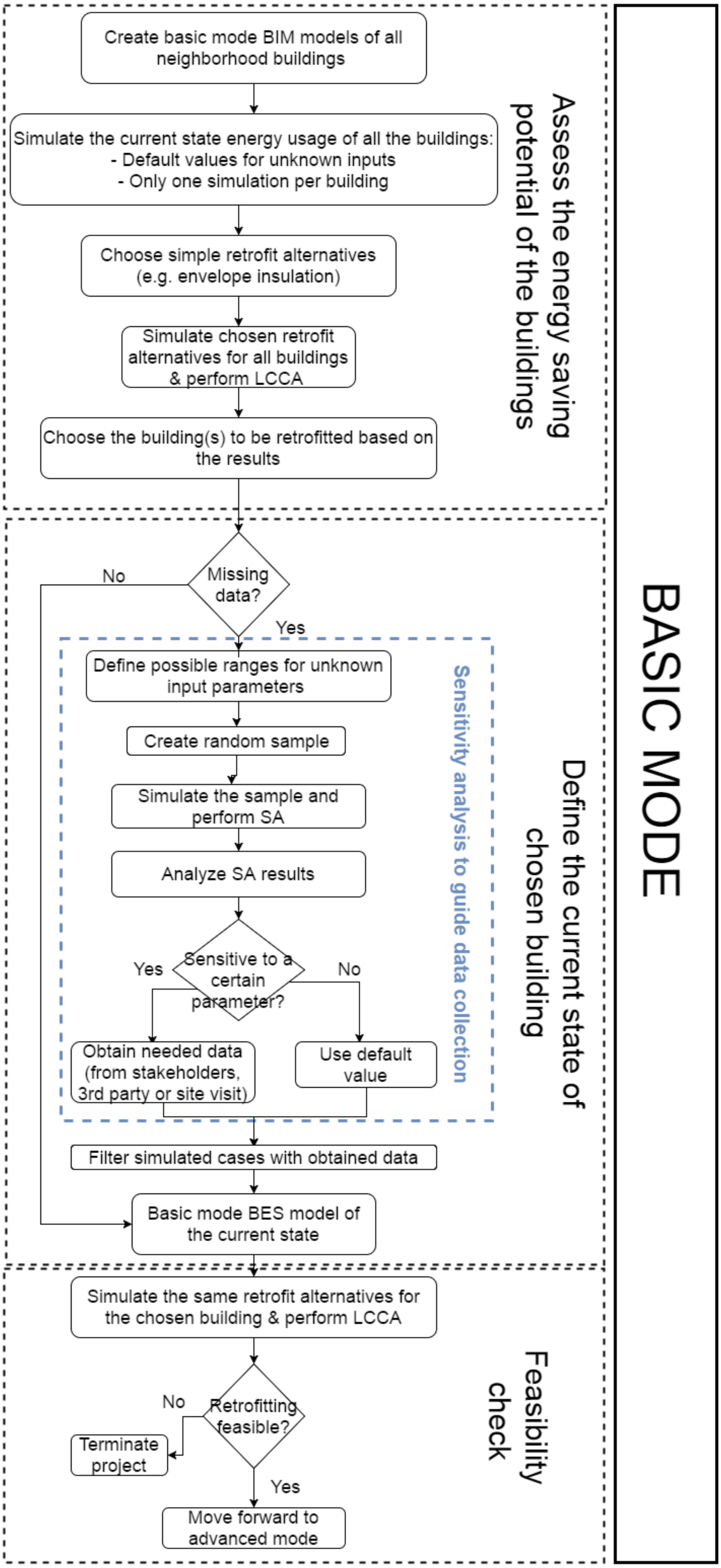


Figure 3.11. Part 1/2 of process flow chart, basic mode.

3.6.2 Advanced mode

In the advanced mode, the process is divided into the following steps (Figure 3.12):

1. Define the current state of the chosen building more accurately
2. Find the optimal retrofit alternative
   2.1. First simulation round with a large number of retrofit alternatives
   2.2. Second simulation round with uncertainty analysis to support decision making

In **the first step**, the current state of the building is defined in a way that it satisfies the requirements of the advanced mode. First, the advanced mode BIM model has to be created for the energy simulation purposes. This means adding windows and doors to their accurate locations in the envelope, as well as defining each individual room in the building with interior walls. At this point, it is likely that some of the needed information about the current state of the building is still missing. If this is the case, then it is possible to perform another sensitivity analysis round to guide the further data collection. For this second sensitivity analysis, it needs to be reconsidered that which parameters are parametrized and how should their ranges be determined. The parameters that showed little significance in the previous sensitivity analysis can be left out, as well as the parameters which are already known. For the still unknown parameters, the ranges should be narrowed down, if possible. For example, if the construction type of the exterior wall is found out, but the accurate U-value still remains unknown, this knowledge can be used to narrow down the previous range of values for the wall U-value. Otherwise, the procedure for the sensitivity analysis is exactly the same as in the basic mode. However, it is possible that sensitivity analysis is not required anymore at this stage, making it possible to skip this part. Once all the needed information has been obtained, the data is inputted into the simulation software, and the energy performance of the building is simulated. The simulated consumption should be compared to measured monthly consumptions in order to verify the energy model. If they do not match sufficiently well, it might be necessary to fine-tune the model. The fine-tuning can be done by varying the parameters that are still not known with full certainty. For example, the infiltration rate and occupancy schedules are often challenging to determine accurately, and thus they can be varied within their possible boundaries in order to match the simulated and measured energy consumption.

The goal of **the second step,** and ultimately of the whole process, is to find the optimal retrofit design alternative. The current state building energy simulation model that was created in the first step, will be used as a base case when comparing different retrofit alternatives. The simulations in this step have been divided into two separate rounds. In the first simulation round, a large number of different retrofit alternatives are simulated, of which a smaller group of promising alternatives is chosen for the next simulation round. In the second simulation round, the uncertainties related to the chosen design alternatives are evaluated, based on which the final decision should be made.

Before any simulations can be performed in the second step, the possible retrofit design alternatives have to be chosen first. In choosing the retrofit alternatives, the requirements set for the retrofitting are the most important aspect to be taken into account. The requirements might be, for example, to reduce the heat energy consumption to a certain level, while improving the indoor conditions to a more satisfying level. In the case that a whole neighborhood is involved in the project, integrated systems for multiple buildings should be considered. For example, multiple buildings might be able to utilize one integrated ground source heat pump. Once the retrofit design alternatives have been chosen, the next task is to define the range of values for these alternatives. For example, which insulation thicknesses and heat pump powers are chosen for the simulations. These ranges should be determined so that they can be carried out in reality. If it is desired to take cost related KPIs into account, it is also necessary to make investment cost estimations for the different retrofitting alternatives at this point.

Once the ranges have been determined and inputted in the simulation software, the actual simulations can be performed. If the number of combinations to be simulated is very high (>1000), a random sample can be simulated in order to save time. Then, sensitivity analysis should be performed from this sample in order to see which of the different retrofit measures have the highest impact upon the results. After analyzing the actual simulation results and the sensitivity analysis results, it is decided whether it is necessary to simulate another random sample. If enough promising design solutions have already been discovered, there might be no need for further samples. However, it might be wise to utilize the sensitivity analysis results to narrow down the input ranges, and thus reduce the number of combinations. For example, if it is noticed that adding insulation to the roof has very little significance, the number of different roof insulation thicknesses can be reduced. Or, if it seems necessary to renew windows to satisfy the requirements, the original window can be left out of the simulations. After the new ranges have been defined, another random sample is simulated and analyzed. This iterative procedure can then be carried out for as long as it is necessary. On the other hand, if the number of combinations is low (>1000) it makes sense to simulate all the cases. In this case, the sensitivities can again be analyzed, but it might not be necessary in order to find the optimal cases. Either way, the first simulation round should result in choosing a smaller group (<10) of promising retrofit design alternatives. The best way of finding the most promising alternatives is to visualize the simulated cases in a scatter plot, with conflicting KPIs on the axes, for example, primary energy need on the other axis and LCC on the other axis. Then, the most optimal cases regarding these two KPIs can be found from the pareto frontier. Additionally, the simulated cases should be filtered with the requirements set for the retrofitting in order to leave out the alternatives with undesirable results.

Next, the smaller group of chosen retrofit design alternatives continue to the second simulation round, in which uncertainty analysis is utilized to support the decision making between these remaining alternatives. In order to analyze the uncertainties related to these alternatives, it is first necessary to define ranges for the uncertain scenario parameters. The most important uncertainties to be taken into account are weather and energy price escalations, but other parameters can also be included, depending upon the nature of the project. For example, the usage schedules of the building might be uncertain. Again, it should be considered carefully what kind of scenarios could be possible, and avoid defining the ranges too narrow or too wide. This is, however, rather challenging because of the unpredictable nature of many uncertain parameters. Once the ranges for the uncertain parameters have been defined, a random sample is again generated for the simulation. If the number of combinations is not too high, it is also possible to simulate every case. Then, the uncertainties related to each of the remaining retrofit design alternatives are analyzed, based on which a decision is made between these alternatives. At this point, it is also beneficial to assess the sensitivity of the energy simulation model to these uncertainties in order to see which parameters are the most responsible for causing these uncertainties.

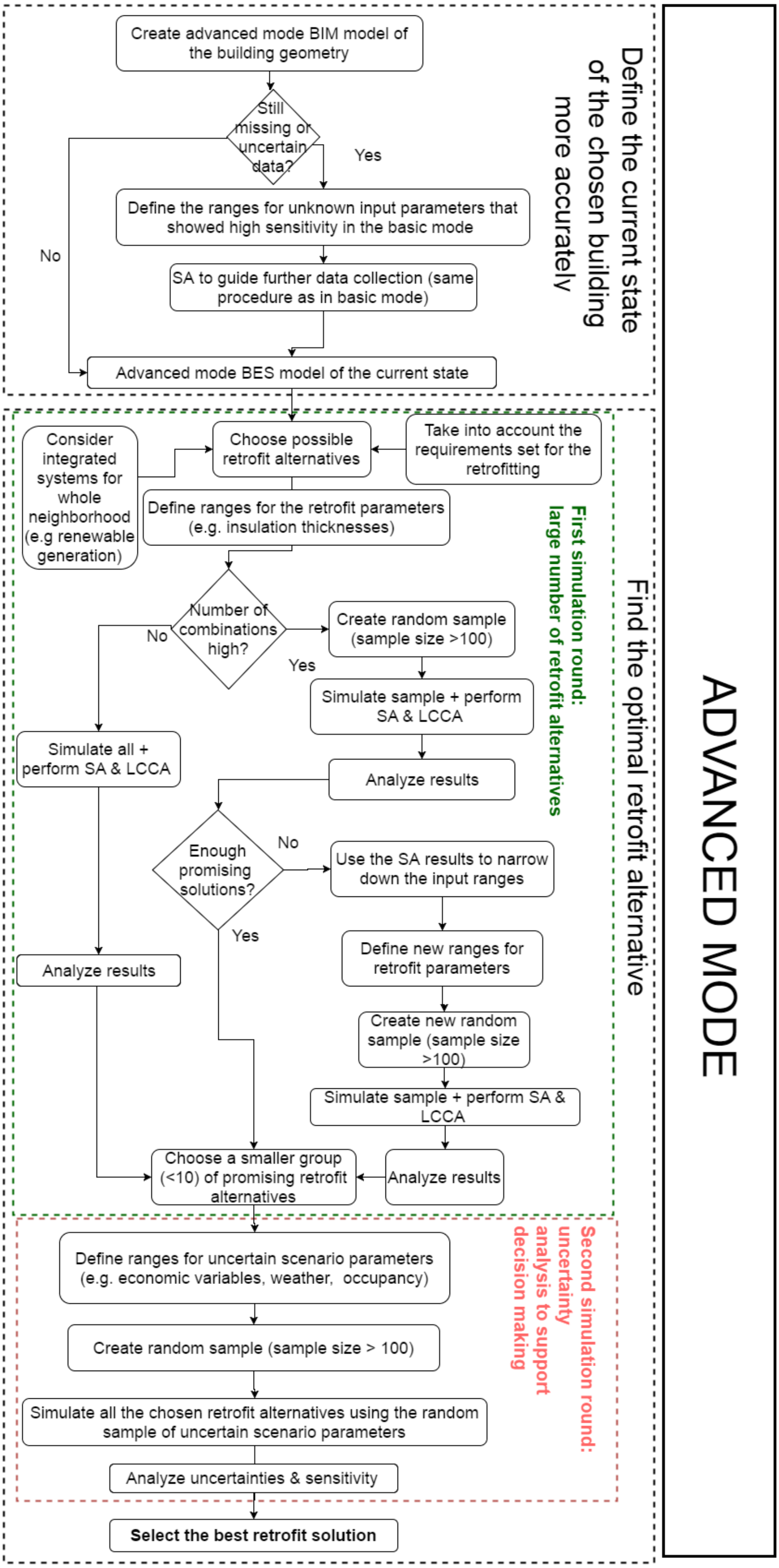


Figure 3.12. Part 2/2 of process flow chart, advanced mode.

4 Piloting of the new process and the advanced methods

Piloting of the new process is presented in this chapter. First, the pilot project neighborhood is described in section 4.1. The actual energy analysis process is divided into sections 4.2 and 4.3 for the basic mode and advanced modes analysis, respectively.

4.1 Description of the pilot project neighborhood

The pilot project neighborhood is located in the city of Seinäjoki, Finland. Seinäjoki is a relatively small city located in the center of South Ostrobothnia (Figure 4.1) with a population of 61,500 residents [58]. The neighborhood consists of four buildings that were originally built in 1930 to serve as county hospital of Seinäjoki, but since the 1980s the hospital moved elsewhere. Today, the buildings are owned by the City of Seinäjoki and are being used for multiple different purposes.

Figure 4.1. Location of the pilot project (Google Maps).

The locations and names of all four building are illustrated in Figure 4.2. The main building (1) is used for educational purposes by the Music School of Ostrobothnia and Seinäjoki University of Applied Sciences. Next to the main building lies another similar building, which is named in this work as the office building (2). It used to be an outbuilding when the neighborhood acted as a hospital, but today it offers space to a dental clinic, health care for students and office space for a few organizations. North of the office building lies a third building, which was originally a boiler house (3) during the time when the buildings were heated by a large wood fired boiler. Today, the buildings are connected to the local district heating network, and the heat distribution room is located in the old boiler house. Additionally, this smaller building is used as an office space by the Parks Department of Seinäjoki and city-owned Marttilan Kortteeri Company, which is responsible for housing the students. The fourth building, Kivirikko house (4), was originally built as an apartment for the director of the hospital. Nowadays, it is used by Mannerheim League for Child Welfare, offering child care services and activities for families with small children.

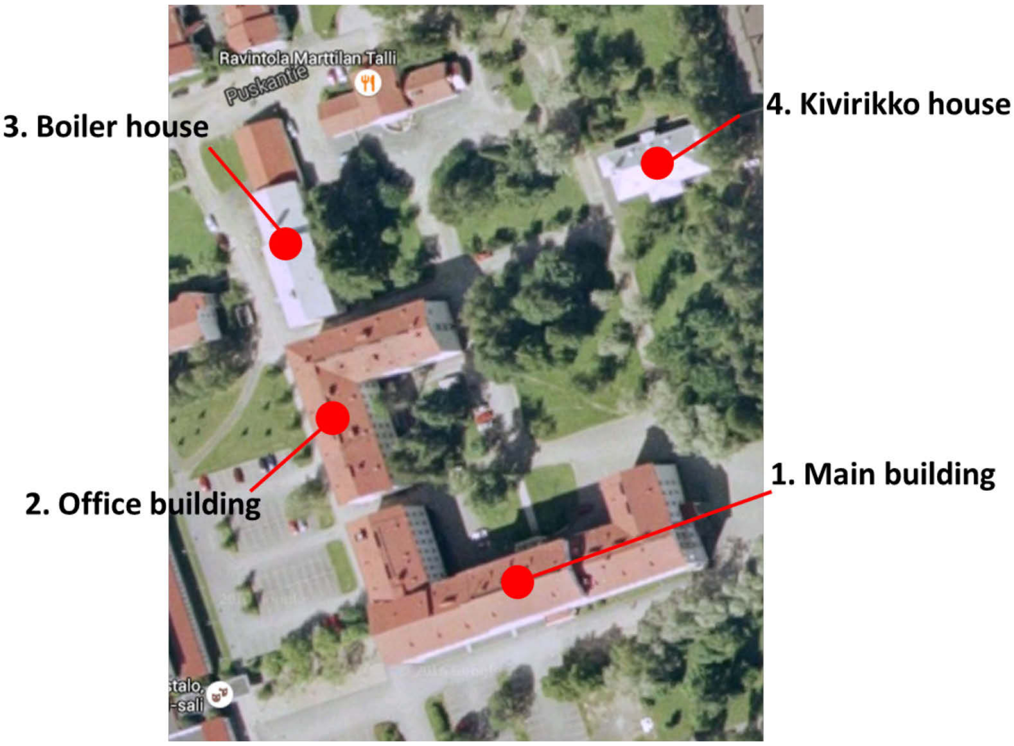


Figure 4.2. The pilot project neighborhood consists of 4 buildings (Google Maps).

Ground level pictures of the building facades in the winter are presented in Figures 4.3 - 4.6. From these figures can be seen that the main building, the office building and the boiler house have been constructed in a similar way. Taking the construction year and appearance into account, the exterior walls are likely to be plastered brickwork. Kivirikko house has a wooden envelope and probably a concrete foundation, based on Figure 4.6. All the buildings have pitched metal-sheeted roofs.

Figure 4.3. Main building, north-facing façade.

Figure 4.4. Office building, north and west-facing facades.

Figure 4.5. Boiler house, east-facing facade.

Figure 4.6. Kivirikko house, north-facing facade.

4.2 Basic mode

The piloting of the basic mode phase of the process is described in this section. First, the initial information that was available at the beginning of the project is presented in Section 4.2.1. Then, the creation of the BIM models used in this mode is described in Section 4.2.2. After this, the energy saving potential of the buildings is assessed in Section 4.2.3, based on which the building to be retrofitted is chosen. Next, the current state of the chosen building is defined in Section 4.2.4, including the sensitivity analysis for data collection and defining the simulation case that best represents the chosen building. Lastly, the economic feasibility of retrofitting the chosen building is checked in Section 4.2.5.

4.2.1 Initial information

At the beginning of the project, there was not much information available about the buildings. Luckily, architectural drawings of the buildings were acquired, which allows much easier generation of the BIM models. Additionally, an employee of the City of Seinäjoki, Puska A. [59], had made a short report about the energy saving potential of these buildings, with focus on building automation. In this report, the current state of technical systems is assessed briefly and the energy consumptions of the buildings are compared to statistics. For energy analysis purposes, this report includes some useful information, such as measured consumptions of heat, electricity and water from year 2014, the types and conditions of the technical systems and the use purposes of the buildings. However, specific values are not given to any parameters that are needed in the energy simulations. Moreover, the neighborhood has only one combined heat energy meter for all the buildings, making it more difficult to calibrate the energy simulation models. Data about many important parameters, including air flow rates, schedules of air handling units and renovation history of the building, was still missing at this point. Thus, many default values from the regulations or building stock statistics had to be used.

Building specific information known at this point is summarized in Table 4.1. In addition, information that applies to all the buildings is the following:

- All buildings are heated by district heating and old cast iron radiators.
- The buildings do not have cooling.
- The construction of the buildings was finished in 1930.

Table 4.1. Initial information about the buildings at the beginning of the project.

Building	Building type	Building volume [m³]	Ventilation system type	Quantity of air handling units	Measured electricity consumption [kWh]	Measured heat consumption [kWh]
Main building	Educational building	28 310	Mechanical with heat recovery	3	418 050	no data
Office building	Office / dental and health services	14 404	Mechanical with heat recovery	3	135 602	
Boiler house	Office	4 550	Natural ventilation	0	48 847	
Kivirikko house	Day care center	1 508	Mechanical with heat recovery	1	10 180	
All buildings	-	48 772	-	7	612 679	1 768 963

4.2.2 BIM models for energy simulation

The basic mode BIM models of the buildings were created with MagiCAD Room software. With this software it is fast to create accurate technical 3D models of buildings by having an architectural drawing as a reference file and drawing the walls on top of the drawing. The basic mode models are very fast to create since only exterior walls, roofs and floors are modeled. If architectural drawings are available, the only additional information needed is the floor heights. The construction materials and their thermal properties are defined later in the simulation software; thus it was not necessary to consider them while creating the models. However, the walls were created to match the wall thickness in the architectural drawings. In the basic mode, individual rooms are not modeled, but here the floors were divided into zones by users, based on the space allocation drawing that was available. Figure 4.7 is a snapshot taken from the MagiCAD Room 3D preview without roof, thus revealing the top floor. For this building, the top floor is divided into three spaces, a staircase and office spaces for two different organizations. Once models were ready in MagiCAD Room, they were exported as IFC files, which could then used as input files for the RIUSKA energy simulation software.

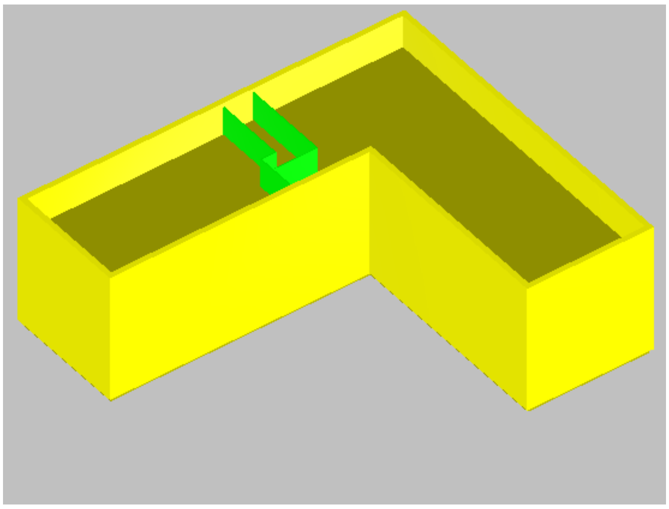


Figure 4.7. Basic mode geometry model of the office building in MagiCAD Room 3D preview.

In the basic mode, windows are not yet accurately modeled. Instead, the window area per exterior wall area is approximated and added to the model. RIUSKA has an automatic feature for adding the windows by giving it the window area percentage. The space boundaries of the model are based on an internal room view, resulting in gaps in the exterior wall between floors and walls when the model is exported as an IFC-file [11]. RIUSKA has also a feature for filling these gaps. Figure 4.8 illustrates the procedure of adding windows and filling the gaps for the main building model in RIUSKA. Figure 4.9 represent the geometric models of all four buildings after the windows were added and gaps filled.

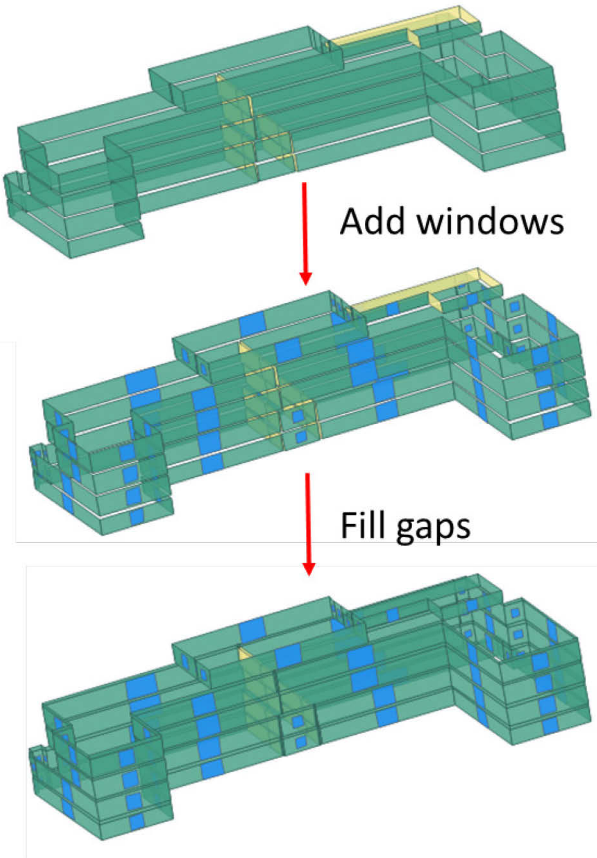


Figure 4.8. Adding windows and filling wall gaps for the main building model in RIUSKA.

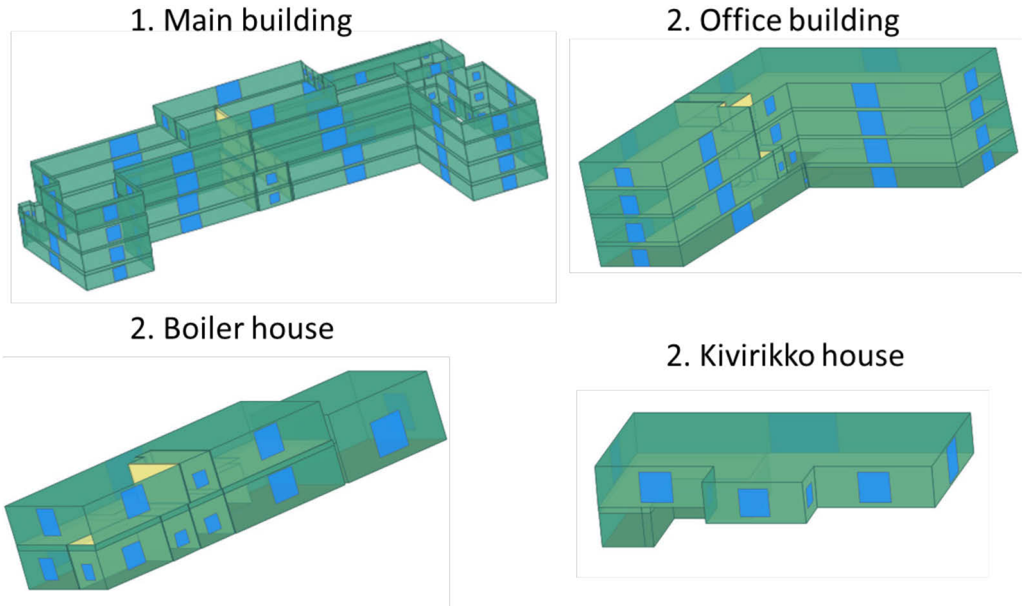


Figure 4.9. Basic mode geometry models of all the buildings in RIUSKA's viewer.

4.2.3 Assessing the energy saving potential of all the buildings

Next, the current state of the buildings is simulated with single simulations, using default values as input parameters. Then, simple parametrized retrofit simulations and LCC calculations are performed for each building. The purpose of doing this is to quickly get a rough estimation of the energy consumptions and to estimate which building has the highest energy-saving potential. In addition, the profitability of retrofitting these buildings is preliminary evaluated. Based on the results, the building to be retrofitted is chosen.

4.2.3.1 Current state of the buildings

In order to assess the energy saving potential of these four buildings, some estimation of their current energy performance is needed. Since most of the needed input data for simulations is still unknown, many default values or values from statistics need to be used. The input parameters used at this point and their sources are presented in Table 4.2. The sources are denoted by colors, and the explanations are given in Table 4.3. Most of the values are default values from the Finnish E-value calculation instructions [60] or from the Finnish building regulations part D3 [25]. These values are meant to be used in official energy calculations if more accurate information cannot be obtained. For example, in the E-value calculation instructions is given a table containing typical design U-values depending on the construction year and building type. Additionally, the Finnish energy certificate guide includes an appendix [61] containing typical design U-values for old existing buildings according to age and type. In this appendix, there was a building type similar to Kivirikko House, but there was not a building type that could represent the other buildings. The exact types of the heat recovery units (HRU) were not known at this point, but it was estimated that they would most likely be rotating heat exchangers. Therefore, the default value given in RIUSKA for HRU supply air temperature efficiency (80 %) was used. The typical efficiency of rotating HRUs is between 60 % and 80 %, so a lower value could have been used as well. Since Seinäjoki is located in the weather zone II, the Finnish building regulations require that the Helsinki-Vantaa Test Reference Year (TRY) 2012 weather file is used.

Table 4.2. Input values used in the first simulations to roughly evaluate the current state of the buildings. The information sources are denoted with colors, which are explained in Table 4.3.

	Building name	**Main building**	**Office building**	**Boiler house**	**Kivirikko house**
General	Building type	Educational building	Office	Office	Day care center
Model geometry	Heated net room area [m²]	6908	3431	625	355
	Volume [m³]	21859	10895	2315	1031
	Exterior wall area [m²]	3522	2250	762	346
	Roof area [m²]	1653	859	367	285,7
	Window area per external wall area	15 %	15 %	15 %	15 %
Envelope & glazing	Exterior wall U-value [W/m²K]	0,81	0,81	0,81	0,64
	Roof U-value [W/m²K]	0,47	0,47	0,47	0,45
	Ground slab U-value [W/m²K]	0,47	0,47	0,47	0,33
	Window U-value [W/m²K]	2,8	2,8	2,8	2,8
	Window g-value [%]	70 %	70 %	70 %	70 %
	Infiltration rate n_{50} [1/h]	6	6	12[a)]	6
HVAC systems	Ventilation type	Mechanical	Mechanical	Natural	Mechanical
	Ventilation rate [dm³/(sm²)]	3	2	-	3
	Heat recovery unit efficiency[b)]	80 %	80 %	-	80 %
	Specific fan power of air handling units [W/(ls)]	2,5	2,5	-	2,5
	Heating set point [°C]	21	21	21	21
	Annual efficiency of district heating system	0,97	0,97	0,97	0,97
	Heating distribution system efficiency	0,9	0,9	0,9	0,9
	Heating system aux. devices electricity demand [kWh/m²a]	13816	6862	1250	710
	DHW heat demand [kWh/(m²a)	11	6	6	11
	DHW transmission efficiency	0,89	0,88	0,88	0,89
	DHW circulation loop heat loss [W/m]	40	40	40	40
	DHW circulation loop length [m/m²]	0,02	0,02	0,02	0,02
	DHW circulation pump power [W][c)]	360	160	80	80
	DHW circulation pump electricity demand [kWh/a]	3154	1402	701	701
Loads	People heat load [W/m²]	14	5	5	14
	Equipment heat load [W/m²]	8	12	12	8
	Lighting heat load [W/m²]	18	12	12	18
Schedules	Building usage time in weekdays (sat - sun closed)	8:00 - 16:00	7:00-18:00	7:00-18:00	8:00 - 16:00
	Internal load annual hours	2088	2871	2871	2088
	AHU annual operational hours [h] [d)]	2610	3393	3393	2610
	Utilization rate [e)]	0,6	0,65	0,65	0,6

Table 4.3. Explanations for the color coding and additional notes about the input values shown in the previous table.

Information sources in the previous table are color coded as follows:	
(green)	Energy saving potential report [59]
(blue)	Basic mode BIM model that was created based on the architectural floor drawings
(light yellow)	Window area was estimated based on the architectural facade drawings
(orange-yellow)	Default value from Finnish building regulations part D3 [25]
(pink)	Equation from Finnish building regulations part D5 [62]
(grey)	Finnish E-value calculation instructions [60]
(light blue)	Finnish energy certificate guide, appendix containing typical values for existing buildings [61]
(peach)	Default value in RIUSKA
Additional notes about the input values in the previous table:	
a) For the naturally ventilated boiler house, air change rate of 0,5 1/h was used by adjusting inflitration.	
b) Supply air temperature efficiency in design conditions, when supply and exhaust air flow rates are equal.	
c) The design flow of DHW was estimated from the architectural drawings, which was then used to calculate the pump power.	
d) It is assumed that the AHUs are turned on one hour before the building opens and is turned off one hour after the building has been closed.	
e) Utilization rate is the average usage of lighting and equipment, as well as average occupation in the building during the usage time.	

Simulating with these default values is fast to do in RIUSKA, since it has a feature that automatically changes the schedules, internal loads and air flow rates to default regulation values according to the building type. However, the U-values, system types, HRU efficiency, domestic hot water usage and HVAC auxiliary electricity demand have to be inputted manually. The constructions were determined by modifying the most appropriate default structures in RIUSKA to get the desired U-values

The simulation results using these input values are presented in Table 4.4. This table presents the purchased heat, electricity and primary energy for each building, as well as the percentages of total consumption. Based on these results, the main building consumes most of the heat and electricity, approximately 60 % of the total consumption. This was a predicted outcome, since the main building is the largest of the buildings. Nevertheless, this would indicate that retrofitting the main building would have the greatest total energy savings. The office building is the second largest consumer of energy, while the consumptions of the boiler house and Kivirikko house are comparatively low.

Table 4.4. Simulation results of the current state of the buildings with default values.

	Purchaced heat			Purchaced electricity			Primary energy (E-value)		
Building name	**[MWh/a]**	**[kWh/ m²a]**	**%**	**[MWh/a]**	**[kWh/ m²a]**	**%**	**[MWh/a]**	**[kWh/ m²a]**	**%**
Main building	1154	167,1	61,9 %	377,3	54,6	58,4 %	1449,2	210	60,3 %
Office building	479,8	139,8	25,7 %	220,1	64,2	34,1 %	710,0	207	29,5 %
Boiler house	156,0	249,6	8,4 %	29,9	47,9	4,6 %	160,0	257	6,7 %
Kivirikko house	74,9	210,9	4,0 %	18,54	52,2	2,9 %	84,0	237	3,5 %
TOTAL	1864,7		**100 %**	645,84		**100 %**	2403,2		**100 %**

In order to assess the accuracy of these results, they are compared to the measured consumptions in Table 4.5. Since the neighborhood has only one shared heat energy meter, only the total heat consumption can be compared. The actual heat demand depends heavily upon the weather of each individual year. Thus, in order to compare the heat consumptions, the measured heat consumption had to be normalized to reflect the same weather conditions used in the simulations. The total simulated heat and electricity consumptions seem to be rather close to the measured values: the total simulated electricity consumption is 5,5 % percent higher and the total simulated heat consumption is 4,7 % higher than the measured value. However, there are large differences between the simulated and measured electricity consumptions of individual buildings. This would indicate that the light and equipment loads are not in reality close to the default values that were used in these simulations.

Table 4.5. Comparison of simulated consumptions to measured 2014 data. Measured total heat consumption is normalized.

	Electricity			Heat		
Building name	**Simulated [MWh/a]**	**Measured [MWh/a]**	**Difference [%]**	**Simulated [MWh/a]**	**Measured (normalized) [MWh/a]**	**Difference [%]**
Main building	377,3	418,05	-9,7 %	1154	no data	-
Office building	220,1	135,05	63,0 %	479,8	no data	-
Boiler house	29,9	48,857	-38,8 %	156	no data	-
Kivirikko house	18,54	10,18	82,1 %	74,94	no data	-
TOTAL	646	612	5,5 %	1865	1780	4,7 %

4.2.3.2 Simple retrofit simulations and LCCA

In order to further assess the energy saving potential of these four buildings, simple retrofit simulations and life cycle cost analysis (LCCA) were performed. The chosen retrofit alternatives are presented in Table 4.6, including five alternatives for both exterior wall and roof, as well as three alternatives for windows, resulting in the total combination of 75 different alternatives. The same alternatives are used for all the buildings. These are fast to simulate simultaneously in RIUSKA with the parametrization feature.

For the exterior walls and roof, these alternatives consist of different thicknesses of additional mineral wool insulation. For the windows, the original default window type (U = 2,8 W/m^{2}K) and two types with better U-values (1,0 and 0,8 W/m^{2}K) were chosen. These retrofit alternatives were chosen because of restrictions in the available investment cost data and restrictions in RIUSKA. Nevertheless, the aim of this step is only to assess the energy saving potential of the buildings and not make any final decision about the actual retrofitting. The U-values of the exterior walls and the roof were determined in RIUSKA by adding the insulation material to the default structure that was used in the previous simulations.

Table 4.6. Retrofit alternatives for the basic mode simulations.

Parameter name	Alternatives
External wall type	Default: no insulation (U = 0,81 W/m^{2}K) EW1: 50 mm mineral wool (U = 0,39 W/m^{2}K) EW2: 100 mm mineral wool (U = 0,25 W/m^{2}K) EW3: 150 mm mineral wool (U = 0,18 W/m^{2}K) EW4: 200 mm mineral wool (U = 0,14 W/m^{2}K)
Roof type	Default: no insulation (U = 0,47 W/m^{2}K) R1: 100 mm mineral wool (U = 0,19 W/m^{2}K) R1: 150 mm mineral wool (U = 0,15 W/m^{2}K) R1: 200 mm mineral wool (U = 0,12 W/m^{2}K) R1: 400 mm mineral wool (U = 0,07 W/m^{2}K)
Window type	Default: double-glazed window (U = 2,8 W/m^{2}K and g = 70 %) W1: triple-glazed window with argon filling (U = 1,0 W/m^{2}K and g = 50 %) W1: triple-glazed window with argon filling (U = 0,8 W/m^{2}K and g = 34 %)

After the simulations, LCCA was performed separately with Excel, since at it was not yet possible to calculate costs in RIUSKA at that time. The aim of LCCA at this point is only to roughly evaluate and compare the economic feasibility of retrofitting these buildings in order to decide which building is going to be retrofitted. The net present value (NPV) of investment for each retrofit alternative was calculated using a cash flow statement with a 25-year period and interest rate of 3 %. Energy savings of each retrofit alternative were calculated by comparing the retrofitted consumptions to the base case consumptions (see Table 4.4). The savings from reduced energy consumptions were considered as a positive cash flow in these calculations. Thus, if the NPV is positive, the investment is profitable. Additionally, simple payback times without discounting were also calculated. The used investment cost data and economic variables are presented in Appendix 1.

The retrofit alternatives with the highest NPV for each building are listed in Table 4.7. Based on these results, it would seem profitable to retrofit all four buildings. The simple payback times are less than five years for each building. With the investment cost data used here, it would not seem profitable to retrofit windows for any of the four buildings. Adding insulation to the exterior walls and the roof, however, seems profitable. The highest NPV per floor area is for the boiler house, since it is the only building with natural ventilation, and thus it has the highest heat losses. Nevertheless, since the main building is the largest building, it also has the highest total NPV of investment (341 k€), even though its NPV per floor area is not the highest. Thus, the main building should be retrofitted first, and is chosen to be further analyzed in this work. In this case, since all the buildings are quite similar, the outcome could rather easily have been predicted without simulations. If the neighborhood had buildings from different ages and types, it would not have been so obvious.

However, these NPV values cannot be heavily relied upon, since the used cost data is likely to be too optimistic, at least for the exterior wall insulation. Here, only material costs and rough estimate for installing the insulation were taken into account (see Appendix 1 for details). In reality, there would be many other additional costs, such as dismantling the old wall structure and adding new plastering. Adding thermal insulation or replacing windows alone is not usually economically profitable. Nevertheless, if building façade has to be renovated either way, then adding insulation should be considered. The goal of this thesis is not to perform accurate LCC analysis, and this was done only for demonstration as a part of the new process. In real projects, more time and efforts would be needed in determining the investment costs.

Table 4.7. Retrofit cases with the highest NPV of investment for each building (basic mode).

Building name	U-values [W/(m²·K)]			Consumptions [kWh/m²]			Investment costs		NPV of investment		Simple payback time [a]
	Window	Wall	Roof	Heat	Electricity	E-value	[€/m²]	[k€]	[€/m²]	[k€]	
Main building	2,78	0,14	0,12	107,7	54,6	169	13,3	92	49,32	341	3,70
Office building	2,78	0,14	0,12	82,8	64,2	168	14,5	50	45,70	157	4,20
Boiler house	2,78	0,14	0,12	139,3	47,9	179	29,7	19	86,84	54	4,44
Kivirikko house	2,78	0,13	0,15	137,3	52,2	185	20,5	7	57,14	20	4,60

4.2.4 Defining the current state of the main building

In the previous section, the energy saving potential and economic feasibility of retrofitting the buildings was assessed, using default values from regulations and statistics. The main building was chosen to be further analyzed, and thus more information about it is needed. In this section, sensitivity analysis is performed to guide the data collection, and a more precise energy simulation model of the main building's current state is created.

4.2.4.1 Parametrization and defining input ranges for sensitivity analysis

Next, sensitivity analysis will be carried out for guiding the data collection. Data collection should be focused on the parameters proved to be the most influential, while default values could be used for the least influential parameters. In other words, the aim of this sensitivity analysis is to help decide that to which parameters it should be invested time and money for determining them more accurately.

The following parameters were chosen for parametrization: external wall U-value, roof U-value, ground floor U-value, window U-value, infiltration rate (n_{50}), HRU supply temperature efficiency, equipment thermal load, lighting thermal load, air flow rate and building schedules. These parameters and their ranges are presented in Table 4.8. More details about the schedules is given in Table 4.9. For all other input parameters, the same default values that were used before (see Table 4.2) are used in these simulations as well.

At this point, there was no point in parametrizing weather, since the aim is to guide the data collection and to define the current state of the building. The orientation angle of the building was already known from the architectural drawings, and thus it was not parametrized. Heat load from people (i.e. average people density) could also have been parametrized. However, it was excluded because it would be difficult to find better approximate than the value from regulations, and thus its sensitivity was not of interest.

Window area was not parametrized, since the windows will be modeled accurately in the advanced mode.

Table 4.8. Parametrization of input parameters for the sensitivity analysis simulations.

Input parameter	Parameter range
External wall U-value [W/m²K]	0,70 / 0,81 / 1,00
Roof U-value [W/m²K]	0,38 / 0,47 / 0,55
Ground floor U-value [W/m²K]	0,38 / 0,47 / 0,55
Window U-value [W/m²K]	2,8 / 3,3
Ventilation rate [dm³/(sm²)]	1,0 / 1,5 / 2,0
Infiltration n_{50} [1/h]	4,0 / 5,0 / 6,0
HRU efficiency	50 % / 60 % / 70 % / 80 %
Equipment thermal load [W/m²]	5 / 10 / 15
Lighting thermal load [W/m²]	10 / 15 / 20
Schedule, AHU operational hours [h]	2610 / 3132 / 3501
Total number of combinations:	**52488**

Table 4.9. Building usage schedules in the parametrized options.

Schedule option	Building usage time		Building closed for holidays	Utilization rate a)	Annual hours	
	Weekdays	Weekends			AHUs [h/a] b)	Internal loads [h/a]
Option 1	8:00 - 16:00	closed	No	0,6	2610	2088
Option 2	8:00 - 18:00	closed	No	0,6	3132	2610
Option 3	7:00 - 20:00	10:00 - 12:00	Yes c)	0,6	3501	3196

a) Utilization rate is the average usage of lighting and equipment, as well as the average occupation in the building during the usage time.

b) It is assumed that the AHUs are turned on one hour before the building opens and are turned off one hour after the building has been closed.

c) Building closed for 9 weeks during the summer in option 3.

In choosing the input parameter ranges, statistical information was used for the envelope parameters. For the other parameters, values from regulations were used as a starting point, and complemented with knowledge from other projects and Granlund's experts. The chosen range for each parameter is shortly justified in the following paragraphs.

In defining the range of the **external wall U-value**, Figure 4.10 was used, which presents the statistical values in Finnish public building stock as a function of construction year. The buildings were under construction in the end of 1920s and finished in the year 1930. Thus, based on Figure 4.10, a range of 0,70 – 1,00 W/m²K was chosen for the external wall U-value.

A similar procedure was used in determining the range for the **roof U-value**. Figure 4.11 presents statistical roof U-value for Finnish residential multi-storied buildings as a function of construction year. This figure was used, since there was not a figure like this for the roofs of public buildings. Nevertheless, it was estimated that this figure would give a good enough estimate for the roof U-value, and thus a range of 0,38 – 0,55 W/m²K was chosen.

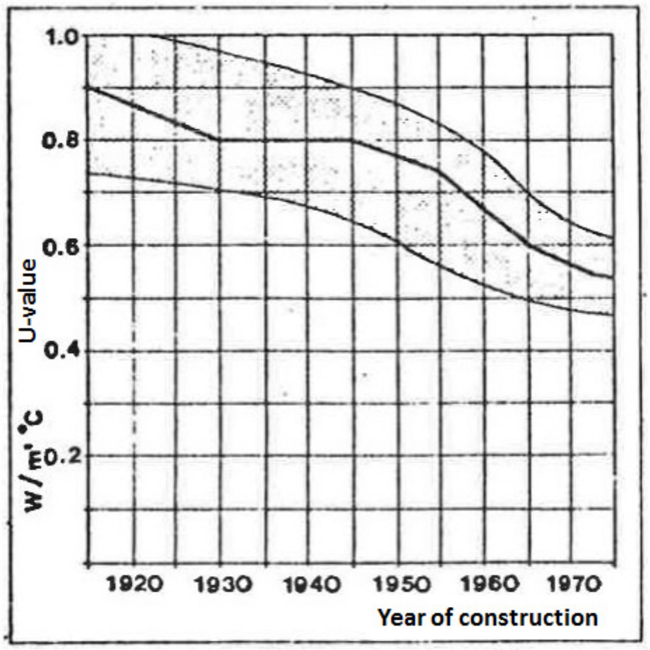


Figure 4.10. Statistical exterior wall U-value in Finnish public building stock as a function of construction year. [61]

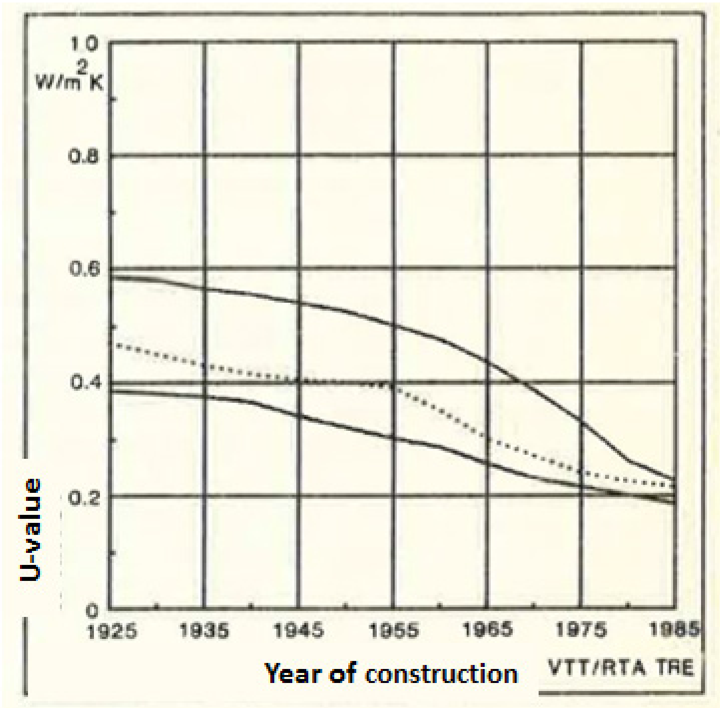


Figure 4.11. Statistical roof U-value for Finnish residential multi-storied buildings as a function of construction year. [61]

For the **ground floor U-value**, this kind of statistical figure was not found. Nevertheless, the old regulation values and values for typical old buildings in [61], as well as the default values in [60] are about the same for ground floor U-value as they are for roof U-value. Therefore, the same range of 0,38 – 0,55 W/m^{2}K was chosen for the ground floor U-value. Furthermore, since the range is the same for the roof and ground floor U-values, their sensitivity is better comparable, as the width of the range has a significant effect on the sensitivity.

Based on the pictures of the building, the windows were estimated to be original old double-glazed windows, which usually have U-values around 3,00 W/m^{2}K. In RIUSKA, there is a database for varying windows, which have to be used in the simulations. In [60], the default **window U-value** for buildings constructed before 1969 is 2,80 W/m^{2}K, which was chosen as the lower limit of the window U-value range. Additionally, another window type with a slightly higher U-value, 3,30 W/m^{2}K, was chosen, since the buildings were constructed long before 1969.

Average **ventilation rate** of 3,00 l/sm^2 has to be used in the E-value calculation for educational buildings [60]. This value was used in the previous simulations. However, based on other projects and knowledge of Granlund's experts, the actual ventilation rate probably is not that high. Instead, a more truthful range of possible values was estimated to be 1,0 – 2,0 l/sm^2.

Since the building is already over 80 years old and the windows were estimated to be original, the air-tightness of the building was expected to be weak. In the Finnish building regulations part D5 [62], for large buildings with weak air-tightness a range of 3 – 7 1/h is given for **infiltration rate** (n_{50}). However, 3 1/h was estimated to be probably too low and 7 1/h probably too high, and thus a range of 4 – 6 1/h was chosen as the most appropriate range for infiltration rate.

The exact types and condition of the HRUs was not known at this point, and thus it was difficult to estimate their efficiency. The most common types for HRUs in Finland are cross-flow plate exchanger and regenerative (rotary) heat exchanger. In [63] , the typical supply temperature efficiency of cross-flow plate heat exchangers is given as 50 – 70 %, and for regenerative rotating heat exchangers the corresponding range is 60 – 80 %. To cover efficiencies of both types, a range of 50 – 80 % was chosen for the **HRU efficiency**.

Ranges for **equipment and lighting thermal loads** were difficult to estimate without any further knowledge about the building. In the Finnish building regulations part D3 [25], values 8 W/m^2 and 18 W/m^2 are given for equipment and lighting thermal loads of educational buildings, respectively. Based on these values and knowledge from other projects, a range of 5 – 15 W/m^2 for equipment thermal load and a range of 10 – 20 W/m^2 for lighting thermal load were chosen.

The **building usage schedule** was still unknown at this point, and thus three different schedule options were chosen for the parametrization (see Table 4.9). The first option is the schedule given in the Finnish building regulations part D3 [25], in which the building is in use 8:00 – 16:00 during weekdays and closed during weekends. In the second option, the building is open later in the evening, having usage time of 8:00 – 18:00 during weekdays and closed on weekends. In the third option, the building is expected to have longer opening hours in the weekdays and a little activity in the weekends as well, but in this option the building is assumed to be closed in the summer for a period of nine weeks. In all three schedule options it was assumed that the AHUs are turned on one hour before the building opens and turned off one hour after the building is closed. With these schedules, the range for AHU annual operational hours is 2610 – 3501h.

4.2.4.2 Sensitivity analysis results

After the input parameter ranges were determined, the energy simulations were performed with RIUSKA. With the ranges presented in Table 4.8, a total of 52488 different combinations were available. Calculating all of these would have taken several days. Therefore, a random sample of 1000 cases was created and simulated. The results from these simulations were used for performing the sensitivity analysis in the KPA tool. The sensitivities of the three most important KPIs are presented and interpreted here: primary energy need, heating energy need and electrical energy need. Primary energy is in principle the same thing as E-value. However, since E-value requires that certain standard inputs are used, this is not the official E-value. Now, it only means that the energy carriers are weighted by their weighting factors. To avoid further confusion, the KPI name "primary energy need" is used when not using standard conditions, and the name "E-value" only when using standard conditions. This building only uses electricity and district heat, which have weighting factors of 1,7 and 0,7. At this point, only these three KPIs were of interest, since the aim is to create a building simulation model that reflects the actual energy performance of the building in its current state.

Figure 4.12 presents the sensitivity analysis results for primary energy need, Figure 4.13 for heating energy need and Figure 4.14 for electrical energy need. The higher the bar is, the more sensitive the model is to changes in that parameter, regarding the certain KPI that has been analyzed. From Figure 4.12 can be seen that regarding primary energy need, clearly the two most significant parameters are airflow rate and building usage schedules. This makes sense, since higher airflow rate increases heat losses through the exchange of air, as well as increase the electricity consumption of fans. Building usage schedule has a great impact, since it includes the operational hours of AHUs and the internal loads. Airflow rate has high impacts on primary energy and heating needs, but not that high on electricity. Schedules, on the other hand, is the most influential parameter for electricity, but not very important for heating energy need. This makes sense, since when the building is closed, the electricity use is minimal, but the heat losses through the envelope will occur regardless.

The third and fourth most significant parameters, regarding primary energy need, are equipment and lighting thermal loads, with nearly equal SRCs. They affect greatly the electricity consumption of the building (see Figure 4.14), since they form the majority of the building's electricity consumption. Regarding heating energy need (see Figure 4.13), they do not rank as that influential. Nevertheless, since electricity has a high weighting factor in the primary energy need calculation, they get high SRCs for primary energy need as well.

Regarding primary energy need (see Figure 4.12), the fifth and sixth most influential parameters are HRU efficiency and infiltration rate. Both of them have minimal effect on electricity consumption (see Figure 4.14), since they do not directly affect anything that consumes electricity. Airflow rates and loads remain the same regardless of what values HRU efficiency and infiltration rate have. On the other hand, these two parameters have the highest impact on heating energy need (see Figure 4.13). This is explained by the fact that both parameters have a great effect in the heat losses caused by ventilation.

The U-values of the building envelope seem to be the least influential parameters in terms of primary energy need (see Figure 4.12). The U-values of walls and windows seem to be the most influential of the envelope components, with SRCs almost as high as infiltration and HRU. They both have very little effect on electricity consumption (see

Figure 4.14), since they mostly affect the heat losses through the envelope. In terms of heating energy need, however, they are rather influential, being the fourth and fifth most significant parameters (see Figure 4.13).

The U-values of ground floor and roof are the least influential parameters for all three KPIs. This is explained by the relatively small area of ground floor and roof compared to wall area. Windows also have small area compared to the exterior wall. However, their U-values are much higher than the U-values of other envelope components, resulting in greater influence.

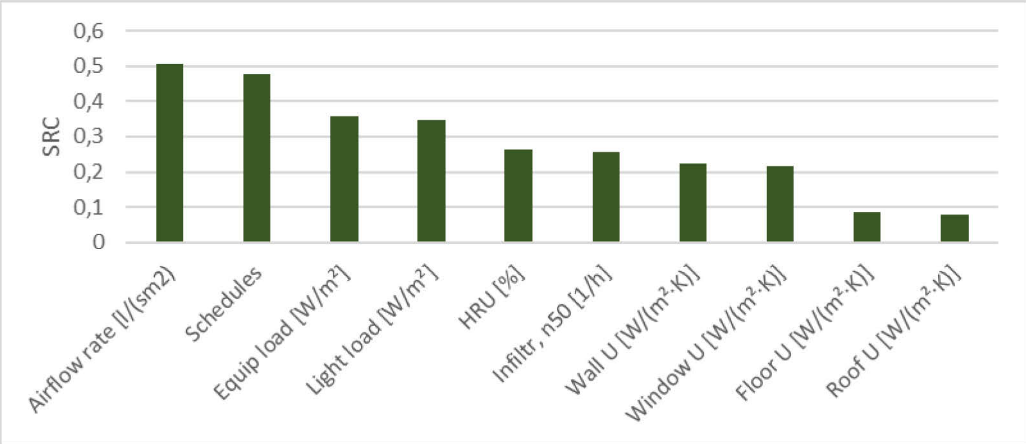


Figure 4.12. Basic mode sensitivity analysis results (SRCs) for primary energy need.

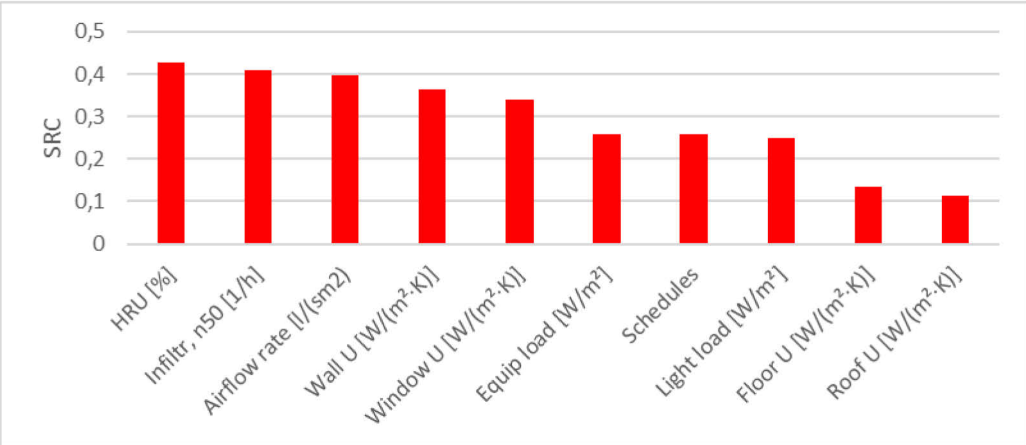


Figure 4.13. Basic mode sensitivity analysis results (SRCs) for heating energy need.

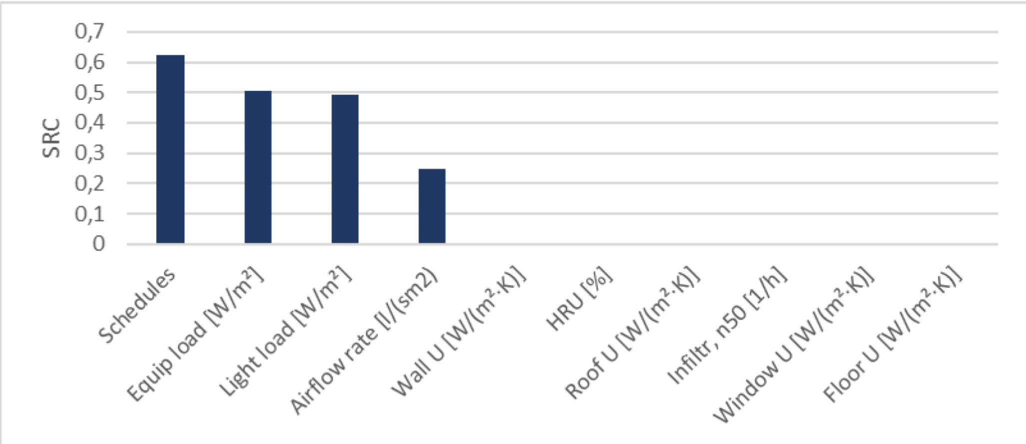


Figure 4.14. Basic mode sensitivity analysis results (SRCs) for electrical energy need.

As conclusion, the most significant parameters affecting this buildings energy performance appear to be usage schedules and airflow rate. Also, equipment and lighting loads show high importance, especially in terms of electrical and primary energy need. Thus, efforts should be made in data collecting especially concerning these parameters. In addition, HRU efficiency, as well as the U-values of walls and windows show rather high significance, mainly regarding heating energy need. Therefore, it would be advisable to find more accurate data about these parameters as well. Infiltration rate is an important parameter as well, but obtaining accurate value for infiltration rate would require costly measurements. Nevertheless, a seasoned energy auditor could give a better estimate for it during a site visit. The U-values of floor and roof showed little significance, and thus default values or rough estimates could be used for them.

4.2.4.3 Data gathering and filtering the results

Since the main building is in reality going to be retrofitted in the coming years, the City of Seinäjoki had ordered a property condition assessment for the building. The assessment was completed during the making of this thesis, shortly after the sensitivity analysis for data collection was ready. Thus, it was convenient to utilize the information from this assessment. However, since the aim of this assessment was to evaluate the current condition of the building and needed repairs, it did not fully concentrate on the energy performance aspects. Nevertheless, important information was obtained, even though for most parameters no exact values were given.

The assessment included the renovation history of the building, which was very important to know in order to get a better picture of the current condition of the main building. The renovation history and changes made are the following:

- 1980s - Renovation of interior spaces from hospital use to educational purposes.
- 1986 - Renovation of ventilation: added mechanical ventilation (supply and exhaust).
- 2010 - Rain water system and courtyard renovation.
- 2010 - Renovation of roof covering (main building and office building).
- 2015 - Added filters to supply air terminal units.

Most importantly, the assessment contained the operational schedules, air flow rates and HRU types of the AHUs, which are summarized in Table 4.10. Also, it was found out that the AHUs have not been replaced since they were installed in 1986. Thus, they were in poor condition during the inspection and were estimated to be at the end of their useful lifetime. Moreover, some serious faults were detected in the adjustment of the ventilation. The supply air temperatures are too high, causing the air to be mixed less efficiently in the rooms. Two of the AHUs have a regenerative rotary HRU and one has a cross-flow plate HRU. In addition, the AHU serving the music school has a humidifier attached to it, because some of the instruments used there require a certain humidity.

The heat distribution room and the heat exchangers are located in the old boiler room. The heat exchangers are relatively new, and it was estimated that they are not in need of replacement yet. The pipes and their insulation in the building are in varying condition. Some are very old and in poor condition with asbestos insulation, while some are newer with better insulation. The space heating radiators are mainly original cast iron radiators equipped with thermostats, which are still in decent condition.

Table 4.10. AHU information obtained from the property condition assessment.

Name	Service area	Schedule during weekdays	Schedule during weekends	HRU type	Supply air [m³/s]	Exhaust air [m³/s]	Supply air temp. [°C]
TK/PK1	Music school	6.00 - 21.00	9.00 - 13.00	Rotary	4,8	4,8	21
TK/PK2.1	Basement and storeys 1-3	6.00 - 21.00	6.00 - 18.00	Rotary	3,2	3,2	20
TK/PK2.2	4. storey	6.00 - 21.00	6.00 - 18.00	Plate (cross-flow)	2,3	3,2	20
TOTAL					**10,3**	**11,2**	

In terms of the envelope components, the assessment does not contain exact U-values. Nevertheless, it included information about the used materials, which is very advantageous in defining the U-values more accurately. The exterior walls were determined to be solid brick walls consisting of two layers of brick with plastering and paint on the outer side. The walls do not have any insulation material, and it was estimated that their U-value could be between 0,8 and 1,0 W/m^{2}K.

According to the assessment, the windows are original double glazed windows with wooden frames. Because of the old age of the windows, they have poor air tightness, and paint was peeling off from the frames. It was suggested that the windows should be renovated or renewed in the near future. Moreover, they estimated that the costs of renewing the windows could be even less than renovating the old ones. However, the building being protected might add complications and more costs.

During the assessment, there was no documentation found about the foundation of the building. Nevertheless, taking the construction time and place into account, they estimated that the foundation is most probably ground-supported with natural stone or concrete structures. The ground floors were determined to be concrete slabs.

The roofs are pitched tin roofs that are supported by a wooden frame. The attic spaces have a concrete floor, which has later been topped with 200 millimeters of mineral wool. In addition, during the building inspection, it was noticed that the old unused natural ventilation ducts were still open. It was suggested that they should be closed as soon as possible in order to reduce the heat losses through infiltration.

In addition, the assessment contained measured heat and electricity consumptions from the past three years. Unfortunately, this data was only for the whole neighborhood. For heat this was expected, since the neighborhood has only one heat energy meter, but the electricity consumption was given with only one number as well, even though the building has multiple sub-meters for electricity.

With these bits of information, it was possible to filter the earlier simulated 1000 cases and find the case that best represents the building. In Figure 4.15 is visualized all 1000 simulation cases with parallel coordinate plot (PCP). First, these cases were filtered with the knowledge about the heating and electrical energy consumption. The heat consumptions given in the assessment were already normalized. However, since the measured consumptions are for the whole neighborhood, some portion of them needed to be allocated for the main building. Regarding heating energy, the amount allocated for the main building was done based on the previous simulation results summarized in Table 4.4. Thus, 61,9 % of the heat consumption was allocated for the main building. For electricity, the allocation was done based on the measured values in [59] (see Table 4.1), which is 68,2 %. The total measured consumptions and consumptions allocated for the main building are presented in Table 4.11. Based on these allocated consumptions, the possible range for heating energy consumption was determined as 155 - 170 kWh/m^{2}a and for electricity consumption 52 - 62 kWh/m^{2}a. After filtering the previously simulated 1000 simulation cases with these consumption ranges, only 62 cases remained, which are presented in Figure 4.16.

Table 4.11. Measured heat and electricity consumptions, and the portions allocated for the main building.

Year	Normalized heat consumption			Electricity consumption		
	Measured, all buildings [MWh/a]	Allocated, main building [MWh/a]	Allocated, main building [kWh/m^{2}a]	Measured all buildings [MWh/a]	Allocated, main building [MWh/a]	Allocated, main building [kWh/m^{2}a]
2013	1859	1150	166,6	546	373	53,9
2014	1790	1108	160,4	610	416	60,3
2015	1772	1097	158,8	601	410	59,4

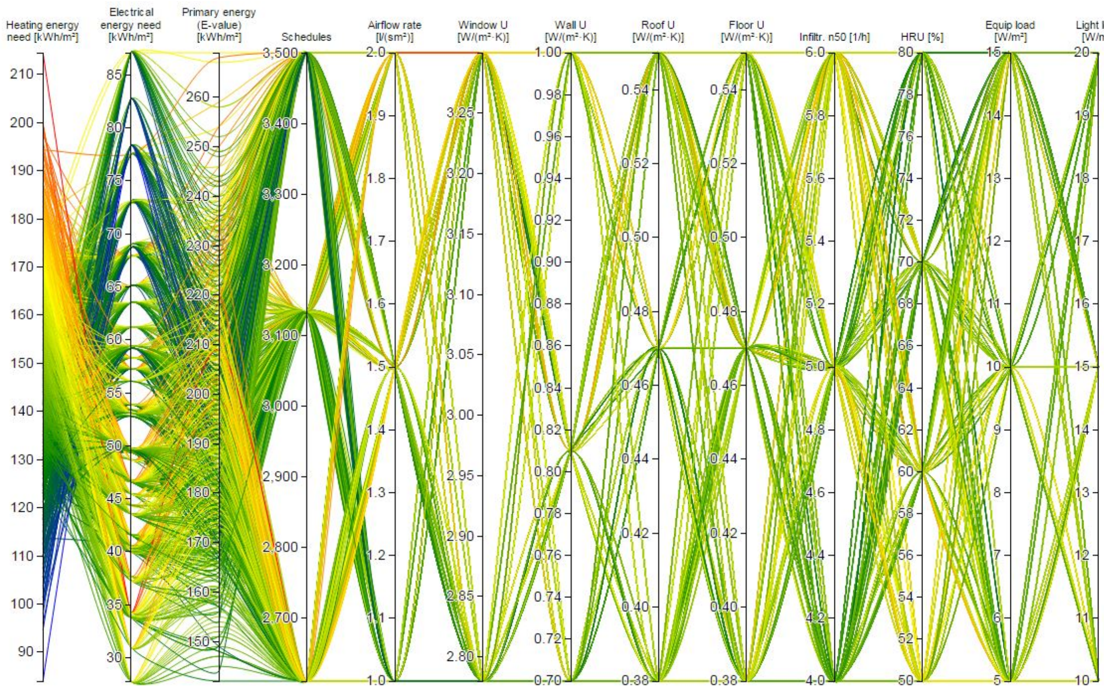


Figure 4.15. PCP visualization of all 1000 cases that were simulated for the sensitivity analysis.

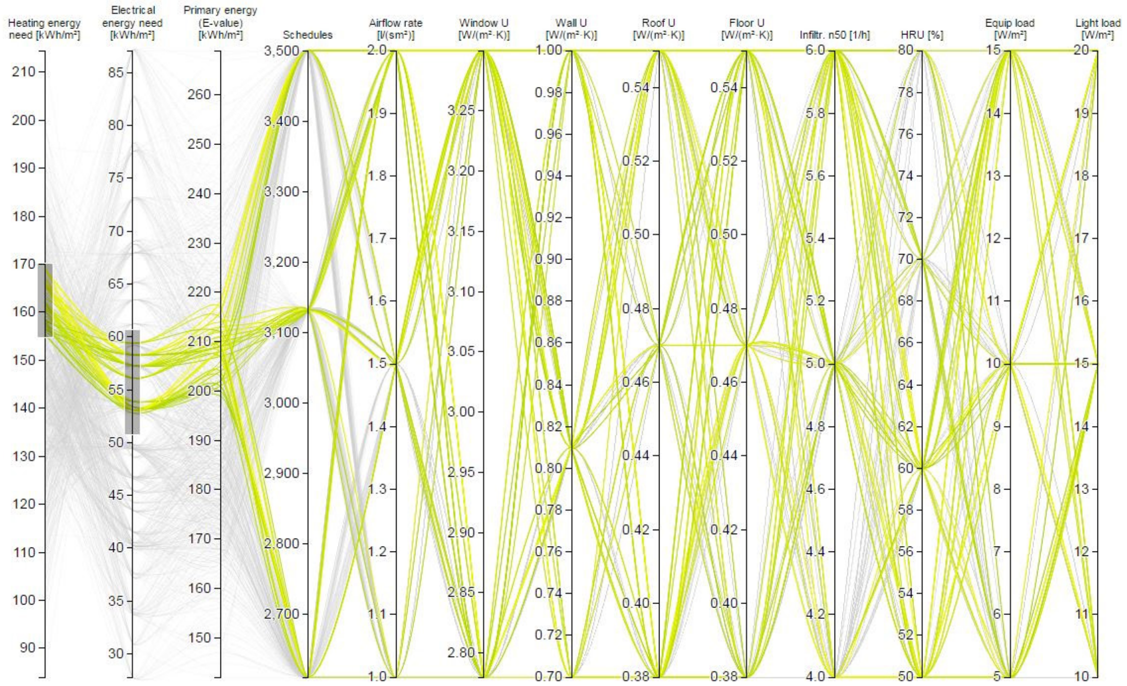


Figure 4.16. Remaining 62 simulation cases after filtering with heating and electrical energy need.

The air flows of each AHU were given in the condition assessment (see Table 4.10), based on which the average air flow rate was calculated to be 1,49 l/sm^2. Thus, the remaining 62 cases were filtered with this knowledge, after which 19 cases remained. Additionally, the AHU operational schedules were given in the condition assessment, and it was noticed that they were rather close to the option 3 (see Table 4.9) that was used in the previous simulations. Schedule option 3 has 3501 operational hours, and the remaining cases were filtered with it. After this, only four cases were remaining.

Taking the age of the AHUs and the poor condition into account, the temperature efficiency of the rotary HRUs is likely to be around 60 - 70%. The efficiency of the plate HRU could be below 50%, since it was very dirty during the inspection. Thus, the remaining cases were filtered with HRU efficiency range of 50 - 60%. This dropped only one simulation case out, leaving 3 possible cases remaining. In order to find only one case, that would best represent the building at this point, the filtering was finished with the window U-value, despite the fact that not much new information about it was obtained. Nevertheless, in the condition assessment it was reported that they are original windows from 1930, and thus it was assumed that their U-value would be closer to the higher one (3,30 W/m^{2}K). After this, only one simulation case remained, which is highlighted in Figure 4.17. Table 4.12 presents the simulation inputs and outputs of this one case. Other parameters, that were not parametrized in the sensitivity analysis, are the same as before (see Table 4.2).

As demonstrated here, the benefits of this kind of sensitivity analysis is manifold. The sensitivity results can be used to orient the data collection process, and the simulated cases can then be further utilized by filtering them to find the case that best represents the actual building. Thus, additional simulations are not necessarily needed even if all the data is not acquired.

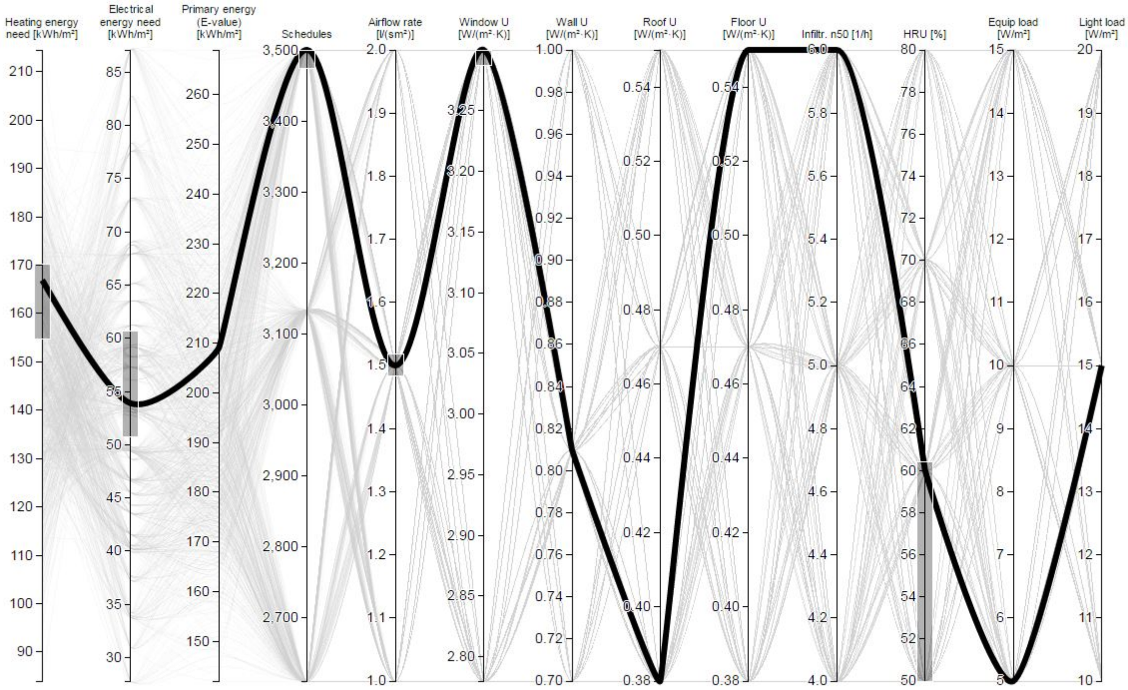


Figure 4.17. The simulation case best representing the actual building after filtering with schedules, air flow rate, HRU efficiency and window U-value.

Table 4.12. Inputs and outputs of the simulation case best representing the actual building (case highlighted in Figure 4.17).

Inputs		
Envelope & glazing	**Exterior wall U-value [W/m²K]**	0,81
	Roof U-value [W/m²K]	0,38
	Ground slab U-value [W/m²K]	0,55
	Window U-value [W/m²K]	3,33
	Window g-value [%]	48 %
	Infiltration rate n_{50} [1/h]	6
HVAC	**Ventilation rate [dm³/(sm²)]**	1,5
	Heat recovery unit efficiency[a)]	60 %
Loads	**Equipment heat load [W/m²]**	5
	Lighting heat load [W/m²]	15
Schedules	**Building usage time in weekdays**	7:00 - 20:00
	Building usage time in Weekends	10:00 - 12:00
	Building closed (for summer holidays)	9 weeks during July - August
	Internal load annual hours	2967
	AHU annual operational hours [h] [b)]	3501
Outputs (KPIs)		
Heating energy need [kWh/m²a]		165,5
Electrical energy need [kWh/m²a]		53,9
Primary energy need [kWh/m²a]		209

a) Supply air temperature efficiency in design conditions, when supply and exhaust air flow rates are equal.
b) It is assumed that the AHUs are turned on one hour before the building opens and is turned off one hour after the building has been closed.

4.2.5 Feasibility check

The previous retrofit simulations and investment cost analysis (see Section 4.2.3.2) were performed with less accurate input parameters, which might affect the simulation results considerably. Now, a more accurate energy simulation model of the main building's current state has been created through data collection. Thus, the same retrofit simulations and cost analysis should be performed again with this new model in order to ensure that retrofitting the main building still seems economically feasible.

The same retrofit alternatives as before were simulated with the more detailed current state energy model as the base case. Then, LCC analysis was done with Excel, while using the same spreadsheet as a basis. Thus, performing this feasibility check did not take much time. The five cases with the highest NPV of investment, are presented in Table 4.13. The retrofit alternative with the highest NPV (highlighted in green) has now changed compared to the previous simulations. In addition to adding insulation to the walls and the roof, it now seems profitable to retrofit windows as well. However, the NPV of the investment has decreased from 341 k€ to 289 k€. Even so, retrofitting the main building still seems profitable, and it was decided to move forward to the advanced mode. However, this demonstrated that the situation can easily change after defining the current state of the building more accurately.

Table 4.13. Five retrofit alternatives with the highest NPV of investment in the feasibility check for the main building.

Case	U-values [W/(m^2·K)]			Consumptions [kWh/m^2]			Investment costs		NPV of investment		Simple payback time [a]
	Window	Wall	Roof	Heat	Electricity	E-value	[€/m^2]	[k€]	[€/m^2]	[k€]	
1	1	0,14	0,14	92,2	53,9	157	42,3	292	37,5	260	9,23
2	1	0,14	0,12	91,4	53,9	156	43,2	299	37,5	260	9,31
3	3,3	0,14	0,14	119,7	53,9	176	12,4	86	37,5	259	4,33
4	3,3	0,14	0,12	119	53,9	175	13,3	92	37,4	258	4,57
5	1	0,14	0,18	93,3	53,9	158	41,5	287	37,2	257	9,18
Base case	3,3	0,81	0,38	165,50	53,9	208					

Insulation thicknesses:

Wall U [W/(m^2K)]	*Ins. thickness [mm]*	*Roof U [W/(m^2K)]*	*Ins. thickness [mm]*
0,81	*0*	*0,38*	*0*
0,39	*50*	*0,18*	*100*
0,25	*100*	*0,14*	*150*
0,18	*150*	*0,12*	*200*
0,14	*200*	*0,07*	*400*

4.3 Advanced mode

Previously in the basic mode, the energy performance of all four buildings in the neighborhood was analyzed using simple BIM models and default values from regulations and statistics. The main building was chosen as the most promising building for retrofitting, and thus more information about it was collected. Next, the main building will be further analyzed in the advanced mode, which requires that a more detailed BIM model and more reliable building information is used.

First, in Section 4.3.1, the creation of the advanced mode BIM model is described. This is followed by defining the current state of the main building more accurately in Section 4.3.2. Finally, in Section 4.3.3 it is demonstrated how the optimal retrofitting alternative can be found, while at the same time taking uncertainties into account.

4.3.1 BIM model for energy simulation

In the advanced mode, a more accurate BIM model of the building is required that satisfies both CityGML LOD4 and AIA's LOD300 (see Sections 2.1.4 and 3.2.2 for more details). Thus, the envelope of the basic mode BIM model needed to be complemented with windows and doors. Architectural drawings of the facades were available in CAD format, which made their modeling rather easy. In addition, the balconies and shelters were modeled. However, they are not imported into the IFC-file, and thus their existence in the BIM model have only visual meaning. The envelope of the advanced mode BIM model is presented in Figure 4.18.

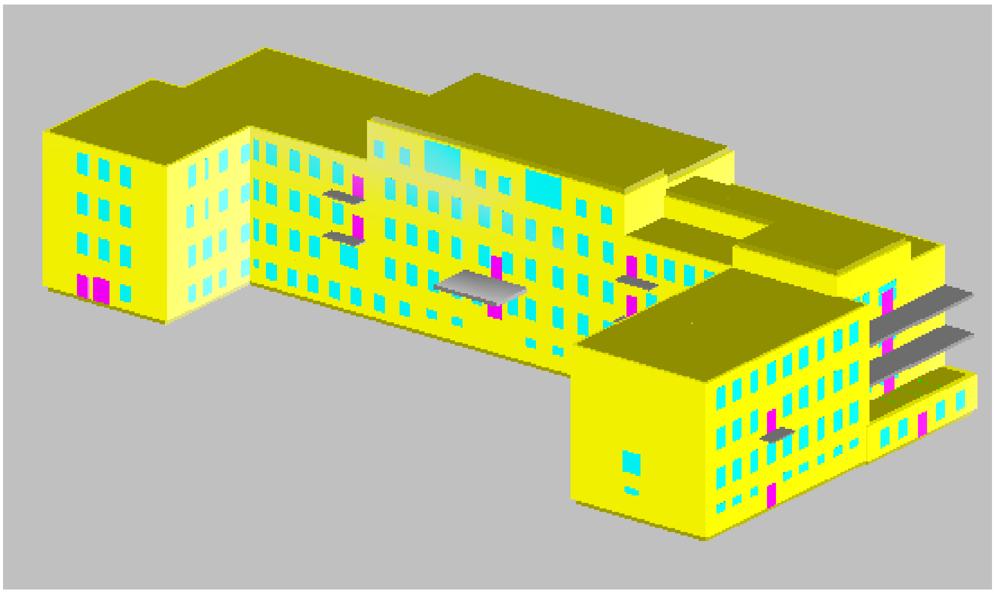


Figure 4.18. Advanced mode geometry model of the main building in MagiCAD Room 3D preview.

In addition to adding components to the envelope, also the interior walls now needed to be modeled in order to form rooms. This was done easily by having the architectural drawings as reference files, and drawing the walls on top of them. However, none of the floors in this building are identical, and the building has interior walls of multiple different thicknesses, which made this task a bit more time consuming. The rooms were named identically to the architectural drawings and all the walls were modeled with actual thicknesses. The interior of the third floor is presented in Figure 4.19.

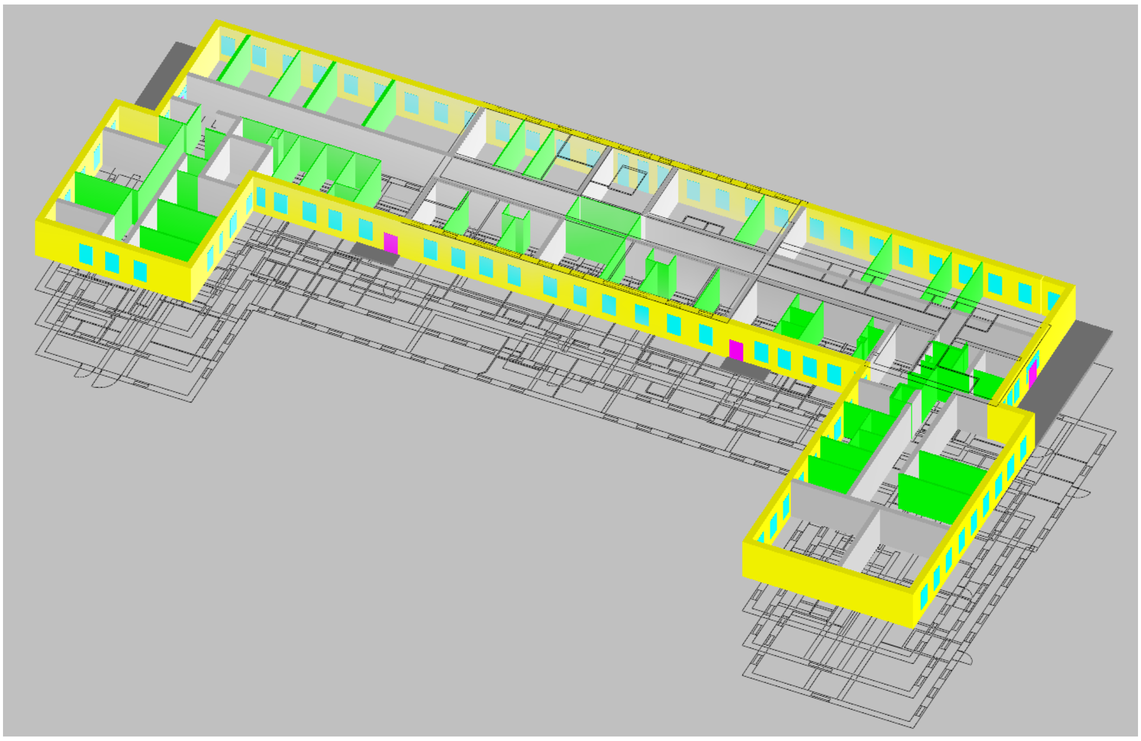


Figure 4.19. The interior of the main building third floor in MagiCAD Room 3D preview.

4.3.2 Defining the current state more accurately

At this point, it was decided that enough information about the building would not be acquired without a site visit. In order to further orient the data collection during the site visit, another sensitivity analysis was performed, while using the information acquired previously to narrow the ranges of the uncertain parameters. After the sensitivity analysis, the needed information was collected, and a more detailed current state energy simulation model was created

4.3.2.1 Parametrization and defining input ranges for sensitivity analysis

After the basic mode sensitivity analysis, some information was obtained from the property condition assessment. Based on these bits of information, the input ranges used in the basic mode (see Table 4.8) can now be narrowed down. Furthermore, if some parameter showed little significance before, it can now be left out of the sensitivity analysis, i.e. only one value can be locked to be used for those parameters. The new ranges, as well as the locked parameters, are presented in Table 4.14.

In the condition assessment, the exterior walls were determined to be 600 mm thick brick walls with plastering, with estimated U-value of 0,8 – 1,0 W/m^{2}K. However, after consulting an energy expert from Granlund, a range of 0,9 - 1,0 W/m^{2}K was chosen to be more accurate range for the external wall U-value. Also, the assessment revealed that the attic spaces have a concrete floor, which has later been topped with 200 millimeters of mineral wool. This structure was generated in RIUSKA software, which gave a U-value of 0,19 W/m^{2}K. Moreover, since the roof U-value did not show high significance in the previous sensitivity analysis, it was locked to have only this one parameter. Regarding windows, it was found out that they have never been replaced, and thus the window U-value was also locked down to have only one value, 3,3 W/m^{2}K.

Table 4.14. Parametrization of input parameters for the sensitivity analysis simulations (advanced mode).

Input parameter	Parameter range
External wall U-value [W/m²K]	0,9 / 0,95 / 1,00
Roof U-value [W/m²K]	0,19
Ground floor U-value [W/m²K]	0,5
Window U-value [W/m²K]	3,3
Ventilation rate [dm³/(sm²)]	1,5
Infiltration n_{50} [1/h]	5,0 / 5,5 / 6,0 / 6,5 / 7,0
HRU efficiency	50 % / 55 % / 60 % / 65 %
Equipment thermal load [W/m²]	5 / 7 / 9 / 11 / 13 / 15
Lighting thermal load [W/m²]	10 / 12 / 14 / 16 / 18 / 20
Total number of combinations:	**2160**

Ventilation rate showed high significance in the previous sensitivity analysis. Nevertheless, the air flow rates of the AHUs were acquired from the condition assessment. Thus the average value of 1,5 dm^3/sm^2 was considered to be certain, and ventilation rate was left out of the parametrization. The air-tightness of the building was estimated to be rather poor, since the windows have not been replaced and draught feelings were reported in the property assessment questionnaires. Moreover, the old natural ventilation shafts were not sealed. Therefore, a range of 5,0 - 7,0 1/h was chosen for infiltration (n_{50}). A range of 50 - 65% was chosen for the HRU supply temperature efficiency, taking into account the age and poor condition of the HRUs. Two of the AHUs have rotating HRU and the smallest one has a cross-flow plate HRU.

For equipment and thermal loads, the same ranges as before were used, since there was no additional information to be found about them in the condition assessment. However, now that many of the parameters had been left out of the parametrization, smaller steps were used than before in order to get more combinations.

The AHU schedules presented in Table 4.10 were used in these simulations. It was assumed that during the holiday season when there is no teaching (July and August), the AHUs are turned off. Also, it was assumed that the building opens one hour after the AHUs are turned on and closes one hour before the AHUs are turned off. Internal loads were assumed to be negligible during the holiday season.

4.3.2.2 Sensitivity analysis results

Like in the previous sensitivity analysis, a random sample of 1000 simulation cases was created and simulated. Figure 4.20 presents the sensitivity analysis results for primary energy need, Figure 4.21 for heating energy need and Figure 4.22 for electrical energy need. From these figures can be seen that the relative importance of these five parameters have remained mostly the same. Thus, the same explanations given in the basic mode sensitivity results apply here as well. Equipment and light load have almost equal SRCs, and are the most influential parameters regarding primary and electrical energy need. Other three parameters have minimal effect on electrical energy need. HRU efficiency is the most important parameter regarding heating energy need, but infiltration has almost as high SRC. These two are also the third and fourth most significant parameters concerning primary energy need. Wall U-value is the least significant parameter of these five, regarding all KPIs. Also it has a relatively smaller SRC than in the basic mode sensitivity analysis, which can be explained by the much narrower range of values it was given.

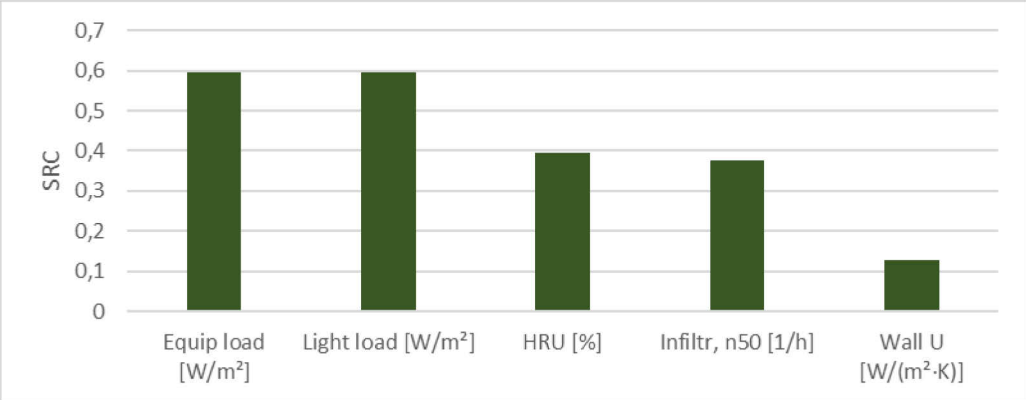


Figure 4.20. Advanced mode sensitivity analysis results (SRCs) for primary energy need.

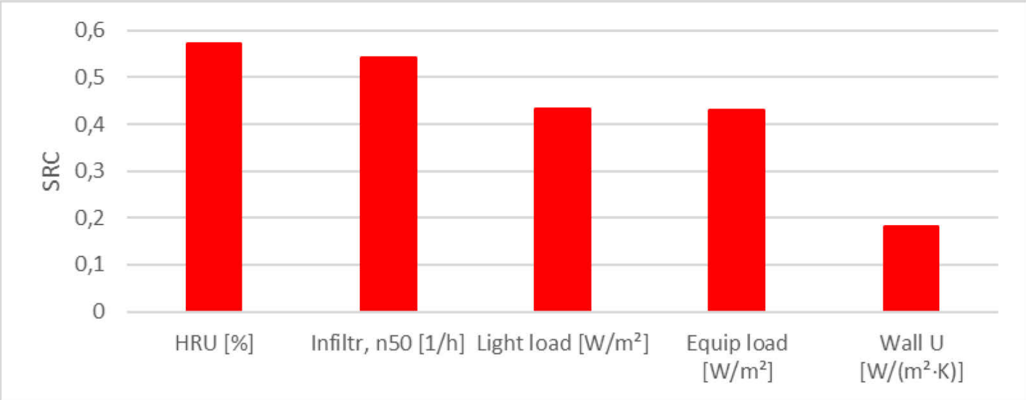


Figure 4.21. Advanced mode sensitivity analysis results (SRCs) for heating energy need.

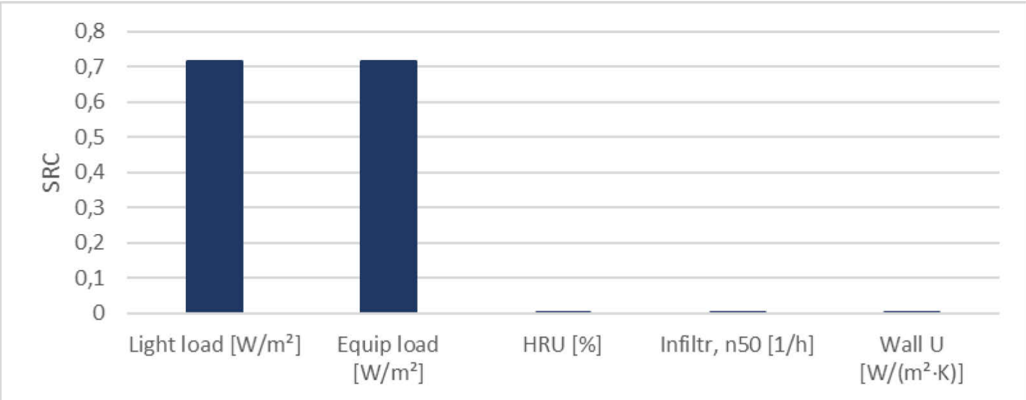


Figure 4.22. Advanced mode sensitivity analysis results (SRCs) for electrical energy need.

As a conclusion, attention should be focused on lighting and equipment loads during the site visit, based on these results. Also HRU efficiency and infiltration rate show high importance, and thus efforts should also be made in gathering more accurate information about them. Wall U-value, however, has very little importance compared to the other parameters, and thus obtaining more accurate value is not necessary.

4.3.2.3 Data gathering from the site visit

The site visit was carried out in the end of June 2016, and thus there was not much activity in the building because of the summer holidays. Only some faculty was present, which allowed easy inspection of the spaces, but any estimates about the normal occupancy or utilization rate of the building could not be made.

The most important source of information from the site visit was the drawings and documents that were found in the basement. These documents were from the mid-1980s, when the building was renovated with mechanical supply and exhaust ventilation. However, the drawings existed only in paper form and they did not fully cover the whole building. During the planning in the mid-1980s the main building was divided into two separate parts; the Music School half and the Seinäjoki University of Applied Sciences (SeAMK) half. For the Music School half, all the necessary drawings were found, including ventilation, electricity and pipe drawings. However, for the SeAMK half, only partial electricity drawings and pipe drawings were found. Nevertheless, these drawings and documents contained important information, especially room specific ventilation rates for the Music School and lighting loads for almost the whole building.

From the heat distribution room, the most important information obtained was the heating control curve from the control unit. Regarding the AHUs, one important note was that they are not in use during Sundays, even though it was reported so in the assessment. Furthermore, it was noticed that the AHUs operate with full power during the summer holiday season, even though the building is almost empty. Since it was a hot summer day, it was not possible to determine the HRU efficiencies of the AHUs.

Not much information was obtained regarding the equipment load in the building, apart from calculating the amount of computers in the computer room. Equipment load was ranked as one of the most important parameters in the both sensitivity analyses performed previously. However, obtaining accurate room specific values would have required visiting each room and calculating all the electrical equipment, for which there was not enough time. Without the means to do any measurements, the site visit did not give any better estimate for air infiltration rate. Nevertheless, because of the original windows and unclosed old ventilation shafts, the building was still estimated to have poor air-tightness, with n_{50}-value likely around 6 1/h. In the advanced mode sensitivity analysis, the wall U-value did not show high importance, and thus obtaining more accurate value did not seem necessary.

In addition to the information obtained during the site visit, the building usage schedules and monthly historical energy and water usage were received from the maintenance personnel later. The building is open in the weekdays from 6.00 to 21.00, but most of the activity happens between 8.00 and 16.00. In the weekends, there is no regular activity, but SeAMK occasionally has used the building also in the weekends. During the summer holiday, the spaces are mainly used by the faculty during office hours.

4.3.2.4 Creating the current state energy model in RIUSKA

After the site visit, the gathered information was utilized in order to create the advanced mode current state energy model of the main building in the RIUSKA software. Previously, in the advanced mode sensitivity analysis simulations, the advanced mode BIM model was used, but now also AHU groups, as well as room specific internal loads and ventilation rates need to be inputted into the model. In addition, a better approximate for domestic hot water consumption is needed.

First, the previous sensitivity analysis simulation cases were filtered with the known information, in a similar way as in the basic mode. These simulation cases cannot be directly used, since they lack the room specific information and AHU groups, but they can give a preliminary idea about the probable values of the still unknown parameters, which in this case are infiltration rate, HRU efficiency, equipment load and wall U-value. From the found electricity documents, the average lighting load in the main building was calculated to be approximately 10 W/m^2. After filtering the 1000 simulation cases with the same ranges for heating and electricity demand, as well as the lighting load, only ten cases remained, which are presented in Figure 4.23. From this figure can be seen the possible ranges for the still unknown variables. U-value can still have any of the three values (0,90, 0,95 or 1,00 W/m^{2}K), which can be explained by its low importance showed in the advanced mode sensitivity analysis. Infiltration rate, on the other hand, only gets values between 5,0 and 6,0 1/h. In addition, most of the cases have HRU efficiency of 65 % and equipment load of 9 W/m^2.

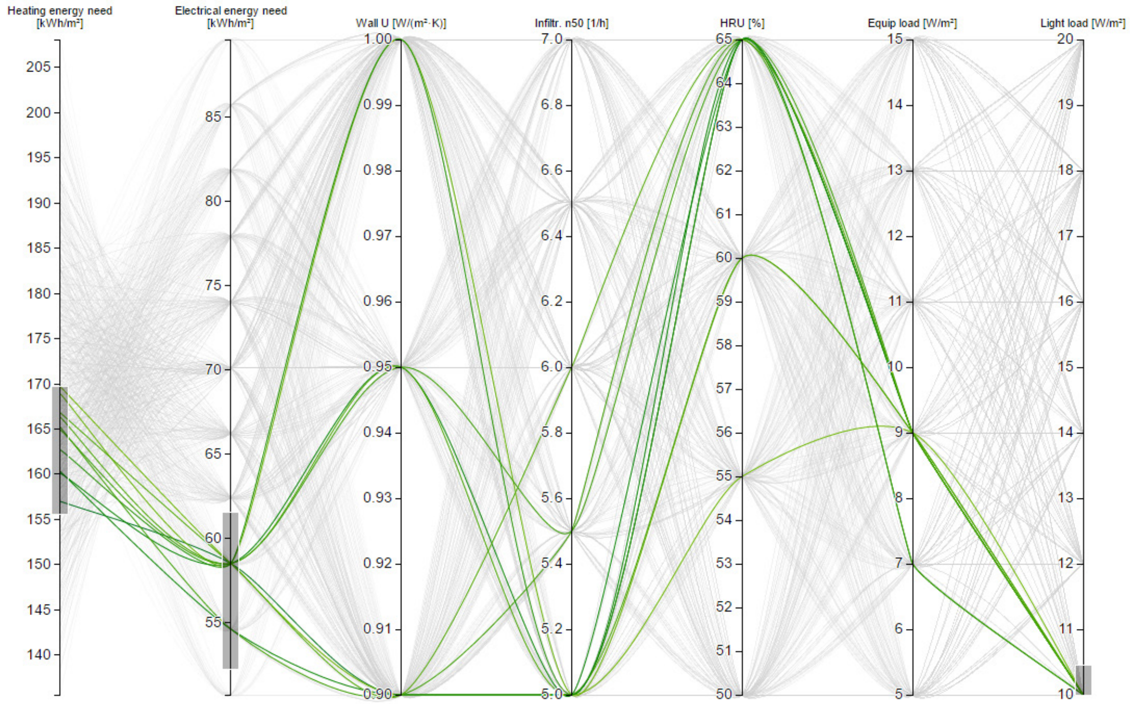


Figure 4.23. Ten remaining cases after filtering the advanced mode sensitivity analysis simulation cases with heating demand, electricity demand and lighting load.

After the filtering, the three separate AHU groups were created with the help of the ventilation drawings. SeAMK half has two AHUs, because the student kitchens in the fourth floor require their own AHU with cross-flow HRU unit. In addition to these three supply and exhaust air AHUs, both halves of the building have a separate exhaust for toilets. At this point, also room specific ventilation rates were inputted. It was easy for the Music School half, since they were marked in the ventilation drawings. However, ventilation drawings for the SeAMK half of the building were missing. Thus, average air flows for each space type were calculated for the Music School half, which were then used for the SeAMK half. Then, they were fine tuned to get approximately the same air flows that were known for the AHUs.

Next, lighting loads for each room were calculated based on the electricity drawings. This was quite time consuming, even with the drawings, since the building had many different types of lighting. Since there was no reliable information regarding the equipment loads in the building, they had to be assumed. Nevertheless, based on Figure 4.23, the equipment load should be around 9 W/m^2 in order to get the annual heat and electricity consumptions to match the measured values. In addition, it was assumed that the Music School half of the building would have less electrical equipment, since most of the class rooms are used for teaching different instruments. Thus, a value of 10 W/m^2 was used for the SeAMK half and 6 W/m^2 for the Music School half as preliminary guesses. Equipment loads in the computer rooms were calculated based on the amount of computers in the room that was visited during the site visit. Regarding the heat loads from people, the same value from regulations (14 W/m^2) that was used in the basic mode simulations was used here. Any better estimation would have been difficult to make without visiting the building again after the summer holiday had ended.

Previously, the default value from regulations had been used for the domestic hot water, which is 11 kWh/m^{2}a. A more accurate value can be calculated based on the historical water consumption. However, similar to heating energy metering, there is only one water meter for all the four buildings. Thus, it was assumed that all the buildings consume approximately the same amount of hot water per square meter. In the instructions given by Motiva [64], it is said that a proportion of 30 % from the total water consumption can be assumed to be used for domestic hot water in non-residential buildings. Using this assumption, a value of 7,5 kWh/m^{2}a was calculated for the domestic hot water.

After all this data was inputted into RIUSKA, one test simulation was performed in order to see how well the simulated consumptions correlate with the measured monthly consumptions. At first, when the same occupancy profile as before was used for the internal loads, the electricity consumption did not match very well with the simulated consumption profile. This was mainly because it was previously assumed that there is no lighting or equipment use during summer time, but based on the consumption profile the electricity consumption is quite high during the summer as well. Thus, a smaller utilization rate was added for the summer time. Then, the usage schedule of the building was fine-tuned until the simulated electricity consumption matched the measured monthly electricity consumption profile. In Figure 4.24 is presented the comparison of simulated and measured electricity consumption after the fine-tuning of the schedules.

After the model had been fine-tuned to match the electricity consumption, the heat consumption still needed to be matched with the measured monthly profile. At first, the simulated heat consumption was higher than the measured. Thus, the simulated heat consumption was lowered by varying the still unknown parameters in their possible ranges. The HRU efficiency was increased, while the wall U-value and infiltration were decreased. After this, also the simulated heat consumption matched the measured monthly profile sufficiently well. The comparison of heat consumptions is presented in Figure 4.25. However, regarding heating energy, it is important to remember that all four buildings only have one combined heating meter, and the proportion allocated to the main building could be inaccurate. Therefore, the main focus here was to get the simulated monthly consumption profile to follow the profile of the measured consumption.

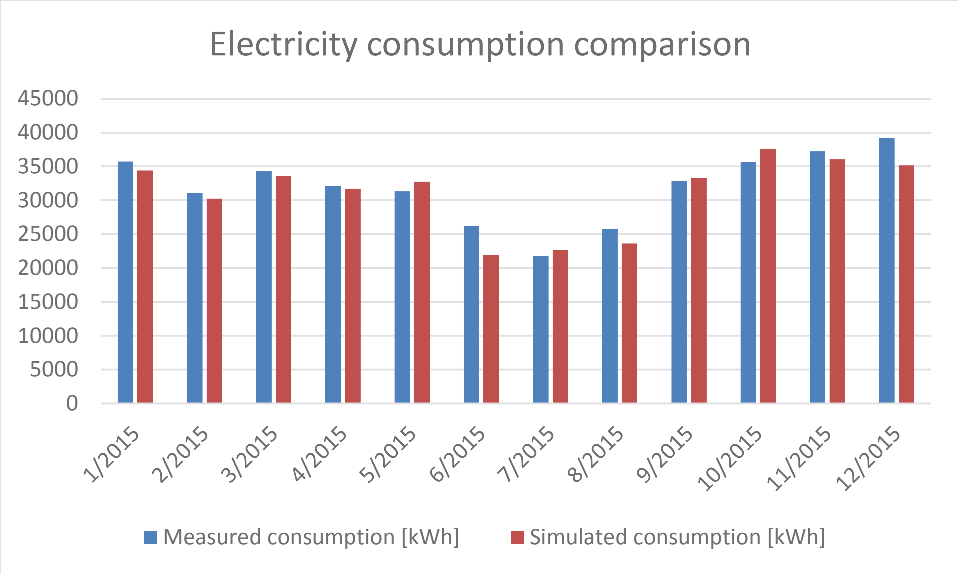


Figure 4.24. Comparison of simulated and measured electricity consumption.

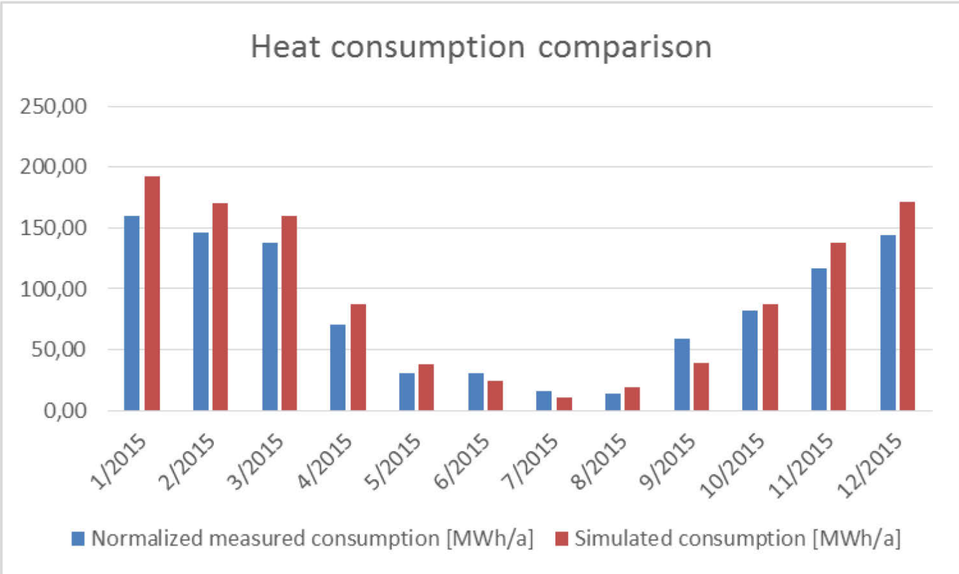


Figure 4.25. Comparison of simulated and measured heat consumption.

All the relevant input parameters for the final current state energy model, along with their sources, are summarized in Table 4.15. Operational schedules, air flows and supply air temperatures for the three AHUs are presented separately in Table 4.16, and the fine-tuned occupancy profiles are presented in Appendix 2. Finally, the simulation outputs (KPIs) are presented in Table 4.17, along with the corresponding outputs from the basic mode simulation. It can be noticed that the outputs of the basic and advanced modes are rather close to each other, even though many of the most significant input values were defined more accurately in the advanced mode.

Table 4.15. Input parameters for the advanced mode current state energy model.

	Parameter	Value	Source
Model geometry	Heated net room area [m^2]	6888	BIM model created based on architectural drawings
	Volume [m^3]	21746	
	Exterior wall area [m^2]	3485	
	Roof area [m^2]	1482	
	Window area [m^2]	765,4	
	Window area per external wall area	18 %	
Envelope & glazing	Exterior wall U-value [W/m^{2}K]	0,9	Condition assessment + estimation based on known structure
	Roof U-value [W/m^{2}K]	0,19	
	Ground slab U-value [W/m^{2}K]	0,5	
	Window U-value [W/m^{2}K]	3,33	
	Window g-value [%]	48 %	
	Infiltration rate n_{50} [1/h]	5	Condition assessment + matching measured consumption
HVAC systems	Ventilation type	Mechanical	Condition assessment
	Ventilation rate, average [dm^3/(sm^2)]	1,5	Ventilation drawings (Music School) and estimation (SeAMK)
	HRU efficiency, rotating[a)]	70 %	Condition assessment + documentation + matching measured consumption
	HRU efficiency, plate[a)]	50 %	
	Specific fan power of AHUs [W/(ls)]	2,5	Default value from [60]
	Heating set point [°C]	21	Default value from [25]
	Annual efficiency of district heating system	0,97	Default value from [60]
	Heating distribution system efficiency	0,9	
	Heating system aux. devices electricity demand [kWh/m^{2}a]	13776	
	DHW heat demand [kWh/(m^{2}a)]	7,5	Calculated from measured water consumption
	DHW transmission efficiency	0,89	Default value from [60]
	DHW circulation loop heat loss [W/m]	40	
	DHW circulation loop length [m/m^2]	0,02	
	DHW circulation pump power [W][b)]	360	Equations from regulations [62]
	DHW circulation pump electricity demand [kWh/a]	3154	
Loads	People heat load [W/m^2]	14	Default value [25]
	Equipment heat load, Music School [W/m^2]	6	Default value [25] + site visit + mathing measured consumption
	Equipment heat load, SeAMK [W/m^2]	10	
	Lighting heat load, average [W/m^2]	10	Electricity drawings

a) Supply air temperature efficiency in design conditions, when supply and exhaust air flow rates are equal.

b) The design flow of DHW was estimated from the architectural drawings, which was then used to calculate the pump power.

Table 4.16. AHU information for the advanced mode current state energy model.

AHU name	Schedule			HRU type	Supply air [m³/s]	Annual operating hours [h/a]
	Weekdays	Saturdays	Sundays			
TK/PK1	6.00 - 21.00	9.00 - 14.00	Off	Rotary	4,768	4175
TK/PK2.1	6.00 - 21.00	6.00 - 18.00	Off	Rotary	3,2	4539
TK/PK2.2	6.00 - 21.00	6.00 - 18.00	Off	Plate (cross-flow)	2,28	4539

Table 4.17. Energy KPIs for the advanced mode current state energy model, with corresponding basic mode values for comparison.

Key performance indicator	Basic mode	Advanced mode
Heating energy need [kWh/m²a]	165,5	165,1
Electrical energy need [kWh/m²a]	53,9	54,2
Primary energy need [kWh/m²a]	209	208

4.3.3 Finding the optimal retrofit solution

Now that the advanced mode energy simulation model of the building's current state was created, the search for the optimal retrofit solution could be initiated. First, some requirements for the energy retrofit need to be set. The actual simulations are divided into two rounds. The first round includes all the retrofit alternatives. Also, a sensitivity analysis is included in the first round in order to assess which individual retrofitting measures have the highest significance. Then, a smaller group of promising alternatives is chosen, which will continue to the second simulation round. The purpose of the second simulation round is to evaluate the uncertainties related to the chosen cases, and finally to determine the most optimal retrofit design alternative.

4.3.3.1 Requirements and choosing the retrofit alternatives

The goal of retrofitting the pilot building is to improve indoor conditions to a satisfying level and make the building more energy efficient, while at the same time taking costs into account. The environmental impact of the building should also be taken into account. Thus, since these targets conflict with each other, the best compromise between them needs to be found. The following three KPIs were chosen as the primary reference values for the retrofit design alternatives: primary energy need (E-value), life cycle costs (LCC) and comfort index.

Primary energy need takes into account both heating and electricity energy demands in one KPI, which makes the comparison much easier. Moreover, it also takes the environmental impact into account by multiplying the energy carriers with specified weighing factors (0,7 for district heating and 1,7 for electricity), which makes it more versatile than simple total energy need. In the Finnish regulations, the requirement for E-value of educational buildings is 0,8 times the original E-value in retrofit projects. E-value is basically the same thing as primary energy need, but it requires calculation in standard conditions, which means using pre-determined schedules and internal loads in the calculation. For this purpose, one more simulation was performed with the current state energy model, using the standard conditions that are required for the E-value calculation. With this simulation, the current E-value of the building was determined to be 216 kWh/m^2, which multiplied by 0,8 gives 173 kWh/m^2. However, since energy efficiency is one of the key issues for this retrofitting project, a requirement was set that **primary energy need has to be below 170 kWh/m^{2}a in all probable conditions**. It needs to be remembered that since standard conditions are not used in the coming simulations, the primary energy needs from these simulations are not the official E-values. Standard conditions are not used when comparing the retrofit alternatives, because it is necessary to reflect the actual usage of the building as much as possible in order to make justified decisions. After choosing the retrofit design alternative, the official E-value will be checked in standard conditions to make sure that the regulation is satisfied.

Cost related parameters are often the most important KPIs for the stakeholder who pays the retrofitting. Thus it is an important aspect to be included in the analysis process. At this point LCC analysis had been implemented in the test version of RIUSKA, supporting three cost related KPIs: investment cost (€), LCC (€) and purchased energy cost (€/m^{2}a). Of these three, LCC is the most descriptive because it includes both investment costs, as well as costs from purchasing energy. Repair and maintenance costs could also be taken into account in the LCC, but they have been left out of the analysis in this thesis. Because the actual retrofitting project had not yet been fully started at the time this thesis was made, the budget was not yet known. Thus, no specific requirements were set for investment costs or LCC. Nevertheless, **LCC needs to be one of the KPIs based on which the retrofit design alternative is chosen.**

The third KPI, comfort index, is included to assess the indoor conditions. Since the building is an educational building, proper indoor temperatures are important in order to provide a good learning environment. Therefore, **a minimum value of 90 % for the comfort index in all conditions was set as a requirement for the retrofitting**. Because the schools in the building are on holiday during the summer, there is very little activity during July and August. Thus, these two months were left out of the comfort index calculation. However, the comfort index takes only temperature into account, since RIUSKA is not capable of CO_2 calculation.

Based on indoor comfort surveys in the condition assessment, the building is hot in the summer and cold in the winter. Furthermore, there were complaints about stuffy air and insufficient ventilation. Also, based on the current state energy simulation, the temperatures can rise above 35 °C in some rooms in the hottest days. However, the school is not in use during the summer, and thus it needs to be considered if cooling is really required, or is higher ventilation rate enough. If cooling is included, then most likely the cooling of supply air would be sufficient and also the most economical choice. It could be an integrated cooling unit for all the buildings, which would reduce the total costs. In RIUSKA, however, it is not possible to simulate multiple building at the same time. During the creation of the current state energy simulation model, it was noticed that the ventilation rates are not high enough to satisfy the current Finnish regulations for educational buildings. **Thus, if the AHUs are decided to be retrofitted, the air flows need to be increased to satisfy these regulations.**

Some retrofitting alternatives could not be included in the simulations because of restrictions in the RIUSKA software. For example, renewable energy generation had to be excluded from the simulations, since it cannot be simulated in RIUSKA. Thus, the same envelope retrofits as in the basic mode (wall insulation, roof insulation and renewal of windows) were included in the simulations, as well as the renewal of the ventilation system with four different alternatives, totaling in 375 different combinations. All the chosen retrofitting alternatives are shown in Table 4.18. The envelope retrofit alternatives are the same as in basic mode, expect for the roof insulation, since it was found out that the roof is already insulated with 200 mm of mineral wool.

Both constant air volume (CAV) and demand controlled ventilation (DCV) systems were included in the simulations. For both systems two different cases were created: one with cooling of supply air and one without cooling. The air flows in the renewed ventilation systems were increased to satisfy the requirements set in the Finnish building regulations part D2 [65]. DCV is a system in which the air flow in certain rooms is varied according to measured CO_2 concentration and/or indoor temperature. Thus, energy can be saved when the air flow is varied according to the need. This can be especially beneficial in school buildings where the occupation of spaces can vary greatly during the day. However, DCV includes additional costs, because it requires sensors to measure CO_2 concentration and temperature. Since RIUSKA is not capable of CO_2 calculation, the DCV types were created in a simpler way by reducing the minimum air flow in certain rooms by 40 % of the regulation value, which is the guideline given in the Finnish building regulations part D3 [25]. This reduction was only done for spaces that supposedly have varying utilization rate during the day, such as classrooms. RIUSKA uses only the hourly indoor temperature to vary the air flow between the given minimum and maximum values (the higher the temperature, the higher the air flow). Thus, it should be noted that these DCV simulations are not highly accurate. On the other hand, even if CO_2 concentrations could be simulated, the usage schedules of the classrooms would be uncertain. Thus, simulating DCV more accurately is rather demanding even with some other simulation software that is able to calculate CO_2 concentrations.

Table 4.18. Chosen retrofit alternatives for the advanced mode simulations.

Parameter	Alternatives	Combinations
External wall type	Original: no insulation (U = 0,90 W/m²K)	5
	EW1: 50 mm mineral wool (U = 0,38 W/m²K)	
	EW2: 100 mm mineral wool (U = 0,24 W/m²K)	
	EW3: 150 mm mineral wool (U = 0,18 W/m²K)	
	EW4: 200 mm mineral wool (U = 0,14 W/m²K)	
Window type	Original: double-glazed window (U = 3,3 W/m²K and g = 48 %)	3
	W1: triple-glazed window with argon filling (U = 1,0 W/m²K, g = 50 %)	
	W1: triple-glazed window with argon filling (U = 0,8 W/m²K, g = 34 %)	
Roof type	Original: 200 mm mineral wool (U=0,19 W/m²K)	5
	RF1: 250 mm mineral wool (U=0,15 W/m²K)	
	RF2: 300 mm mineral wool (U=0,12 W/m²K)	
	RF3: 350 mm mineral wool (U=0,10 W/m²K)	
	RF4: 400 mm mineral wool (U=0,09 W/m²K)	
Ventilation system type	Case 0: Current ventilation system (CAV)	5
	Case 1: **CAV** system, air flows to satisfy current regulations, no cooling	
	Case 2: **CAV** system, air flows to satisfy current regulations, **with cooling** of supply air	
	Case 3: **DCV** system (average 40 % lower air flows assumed), no cooling	
	Case 4: **DCV** system (average 40 % lower air flows assumed) **with cooling** of supply air	
	Total combinations	375

4.3.3.2 First retrofit simulation round

In this first simulation round, all the 375 retrofit design combinations specified in Table 4.18 were simulated. The purpose is to compare the energy performance, comfort index and LCC of these different combinations, and ultimately to choose a smaller group of 5 - 10 promising retrofit design alternatives for the second retrofit simulation round. Furthermore, sensitivity analysis will be used to analyze which separate retrofit measures have the highest impact on the performance of the building.

The same investment cost data that was used in the basic mode is used here for the envelope components, which can be found in Appendix 1. The investment costs of the different ventilation systems were obtained from a dimensioning and LCC software "Future ++". This software has been developed by an air handling unit manufacturer Koja Ltd. It allows choosing a proper AHU from their selections, based on the needed air flows and functionalities. In this work, AHUs with the lowest investment costs were chosen for each system. More details about the chosen AHUs and their investment costs, as well as the cooling system costs, can be found in Appendix 3. Again, it should be noted that the investment cost data used in this work should not be heavily relied upon. These are just approximate costs, mostly based on Granlund's internal documents. The costs can vary a great deal depending upon the project. In many cases, the only way to get accurate values for investment costs is by invitation for bids, which was not yet possible during the writing of this thesis. Similar to the basic mode, a time period of 25 years and interest rate of 3 % was used in the LCC calculation. At this point, energy price escalations are assumed to be 0 %.

4.3.3.2.1 Weighted sensitivity analysis

Here, the sensitivity of the most important KPIs will be briefly analyzed, and the weighed sensitivity analysis will also be demonstrated. The effect of the ventilation system type is problematic for the sensitivity analysis, because there is no clear characteristic value for the types. Between the ventilation system types, the air flows, HRU efficiency and cooling energy demand are different, and thus it is more difficult to determine this characteristic value. This problem was solved by calculating for each ventilation type the air flow that is not heated by the heat recovery unit, as presented in the following equation:

$$C = Q_{TK1} \cdot (1 - \eta_{HRU,TK1}) + Q_{TK2.1} \cdot (1 - \eta_{HRU,TK2.1}) + Q_{TK2.2} \cdot (1 - \eta_{HRU,TK2.2}) \qquad (4.1)$$

where C is the characteristic value, Q is the supply air flow [m^3/s] and η_{HRU} is the heat recovery temperature efficiency. Subscripts *TK1, TK2.1* and *TK2.2* refer to the three different air handling units in the building. However, this characteristic value does not take cooling into account, and thus the actual effect of the ventilation type is probably a bit higher than these results would indicate, especially regarding the comfort index.

First, the sensitivity of the three KPIs, for which requirements were set previously, were analyzed separately. The sensitivity of primary energy need for the different retrofitting alternatives is presented in Figure 4.26, which indicates that ventilation type is clearly the parameter affecting the primary energy need the most. This is an expected result, since the ventilation type includes both the air flows and the HRU efficiency, which both usually have a high effect on the energy performance of buildings. Wall and window U-values are the second and third most significant parameters, with almost equal SRCs. Window g-value and roof U-value do not seem to have much effect. The low impact of roof U-value can be explained by the fact that the roof is already insulated, thus making the range of possible U-values quite narrow. Window g-value has mostly effect on the indoor temperatures during the summer, since it determines how much sunlight is transmitted through the windows. This does not greatly affect the heating demand of the building, and thus it does not have much effect on the primary energy need. This explains also the high impact of window g-value on the comfort index, as can be seen from Figure 4.27. Regarding comfort index, ventilation type does not seem to have as much effect as could have been expected. This is partly explained by the fact that it was not possible to include cooling in the characteristic value of ventilation type. Sensitivity of LCC is presented in Figure 4.28, which shows wall U-value as the most significant parameter. This can be explained by the rather low investment prices for wall insulation used in this work, and by the relatively high savings in heating energy gained from insulating the walls. Ventilation type shows rather high importance regarding LCC as well, while the remaining three parameters seem insignificant.

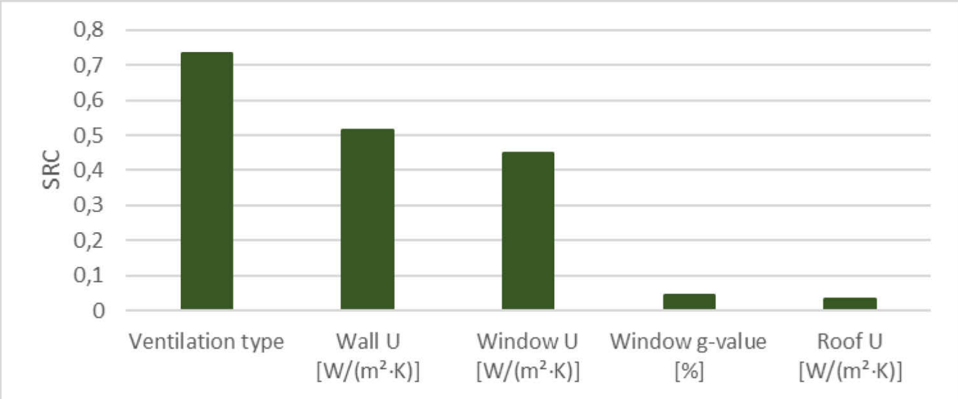


Figure 4.26. Sensitivity of primary energy need for the retrofitting alternatives.

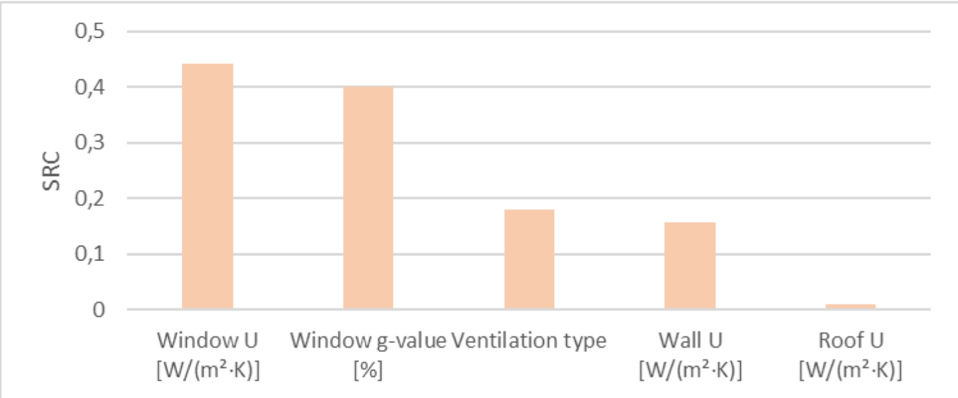


Figure 4.27. Sensitivity of comfort index for the retrofitting alternatives.

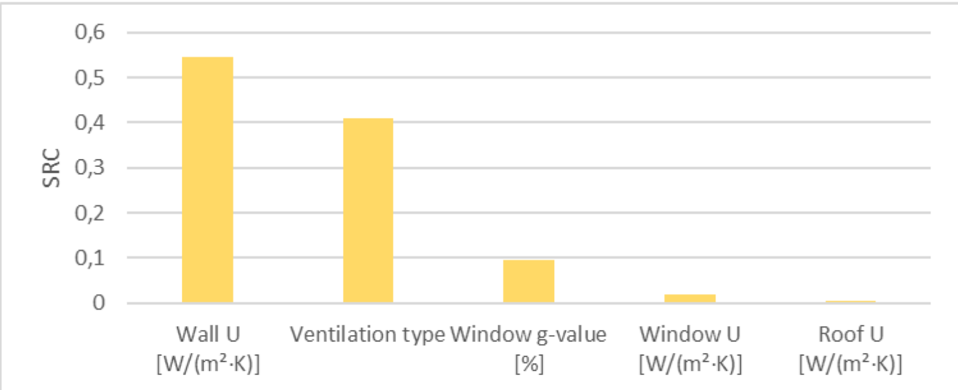


Figure 4.28. Sensitivity of LCC for the retrofitting alternatives.

As was noticed from the previous three figures, sensitivity analysis can give very different results for different KPIs. Thus, it can be difficult to see the overall picture, as multiple conflicting KPIs should be taken into account in the decision making. This problem can be eased by introducing the weighted sensitivity analysis visualization. For the weighting purposes, the KPIs used in the KPA tool were divided into five groups: costs, energy, comfort, emissions and sizing. For these groups, three different weighting scenarios were defined in order to demonstrate the effect of the weighting factors. One scenario focuses more on cost related KPIs, while the other focuses on energy, and the third on comfort. The weighting factors are always subjective, since the decision maker defines them based on his/her subjective point of view. To which group each individual KPI belongs and how these groups are weighted in each of the three scenarios, is presented in Table 4.19. Sizing related KPIs were given no weight in these scenarios, since no requirements were set for them.

Table 4.19. KPIs divided into five groups and their weighting factors in three different scenarios.

Group name	Key performance indicator	Weighting factors		
		Focus on costs	Focus on energy	Focus on comfort
Costs	LCC [€]	50 %	20 %	20 %
	Investment cost [€]			
	Purchased energy cost [€/m²]			
Energy	Total energy need [kWh/m²]	20 %	50 %	20 %
	Heating energy need [kWh/m²]			
	Cooling energy need [kWh/m²]			
	Electrical energy need [kWh/m²]			
	Primary energy (E-value) [kWh/m²]			
Comfort	Comfort index [%]	20 %	10 %	50 %
Emissions	Purchased energy CO_2 [kg CO_2/m²]	10 %	20 %	10 %

The weighed sensitivity analysis results for these three scenarios are presented in Figure 4.29, Figure 4.30 and Figure 4.31. The results are quite similar in the scenarios with focus on costs and focus on energy, with ventilation type as the most important parameter. Window and wall U-value are the second and third most important parameters in both scenarios with almost equal SRCs. When the focus is on costs, window U-value has a bit higher SRC, and the other way around when the focus is on energy. This is because of the higher investment costs for renewing windows. Window g-value and roof U-value are not important in either scenario. The third scenario (focus on comfort), however, shows rather different results. With this kind of weighting, window U-value shows the highest importance. Ventilation type has the second highest SRC value, and wall U-value the third. Window g-value has also a rather high SRC value in this scenario, even though it is only the fourth highest.

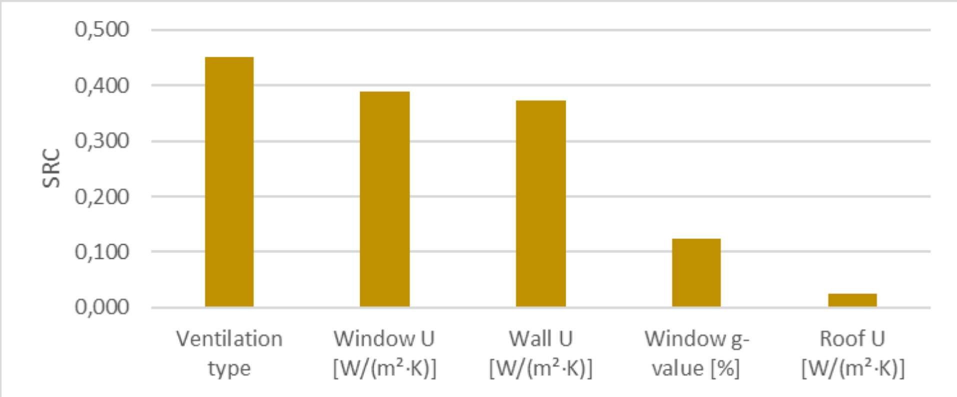


Figure 4.29. Weighted sensitivity with focus on costs.

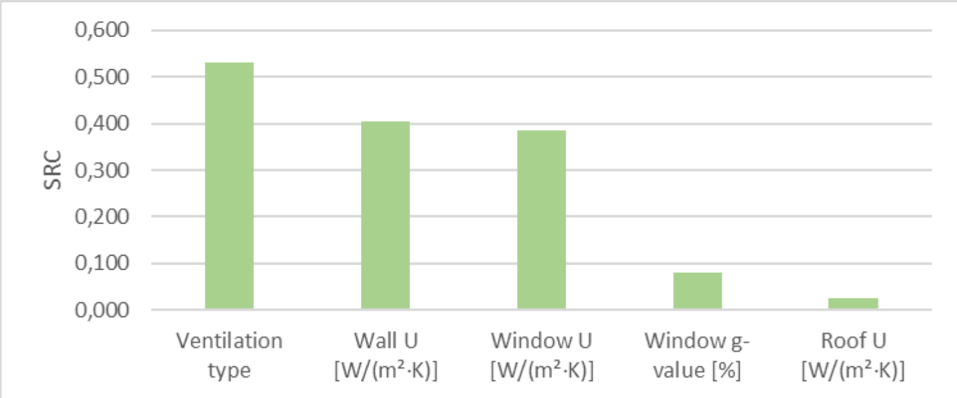


Figure 4.30. Weighted sensitivity with focus on energy.

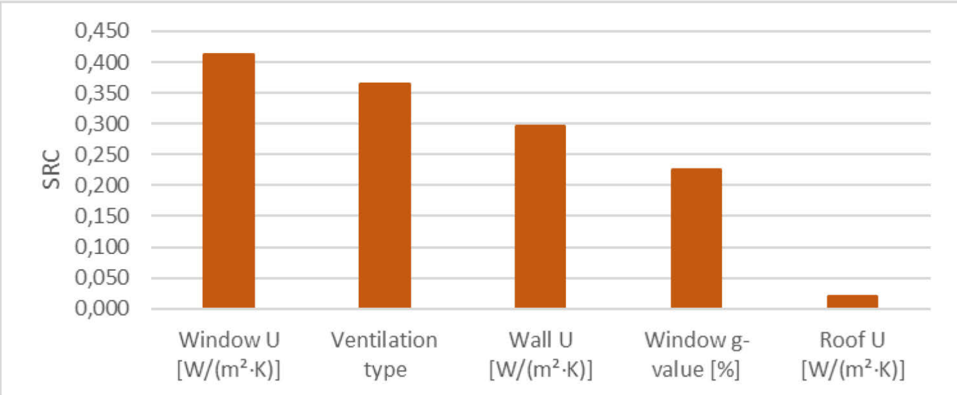


Figure 4.31. Weighted sensitivity with focus on comfort.

It is likely, that weighting scenario with focus on costs (Figure 4.29) is the most realistic of these three scenarios, since costs usually dictate every project. The two other scenarios were included to demonstrate how the choosing of the weighting factors have effect on these combined weighted SRC factors. Nevertheless, as a conclusion can be said that the renewal of the ventilation system would have the highest overall impact, while also renewing the windows and adding insulation to the walls greatly affect the performance of the building. Adding more insulation to the roof, however, does not seem to have much effect. Based on these results, it would be possible to reconsider the retrofitting alternatives. For example, more alternatives could be added for the parameters that showed high importance, and some alternatives could be dropped out of the insignificant parameter. In this thesis, however, this was not done, because with these alternatives enough promising combinations were found.

4.3.3.2.2 Choosing the cases for next simulation round

The 375 retrofitting alternatives were compared with the KPA tool, and six promising alternatives were chosen for the next simulation round. For choosing these six cases, the scatter plot proved to be the best visualization method, with primary energy on the x-axis and LCC on the y-axis. This plot is presented in Figure 4.32, with color coding by ventilation type in order to show the grouping of different ventilation system types in the plot. Also, the current state case is highlighted with thicker outlines and marked with an arrow. Each circle in this figure represents one of the 375 retrofit alternatives. The closer the circle is to the bottom left corner of the plot, the more optimal it is with respect to these two KPIs. From this figure can be seen that the demand controlled ventilation (DCV) types (red and yellow) appear to give more optimal results, especially with respect to primary energy need. The alternatives with the current ventilation system (blue) have the lowest LCC, and some cases even quite low primary energy needs. However, they perform more poorly in terms of comfort index. Also it should be remembered that in the current ventilation system the air flows are not sufficient to satisfy current regulations, which is not taken into account in the comfort index. The cases with the original ventilation system have the lowest LCC values, because of the rather high investment costs included in the renewal of the ventilation system. The cases with renewed constant air volume (CAV) ventilation systems (light and dark green) do not perform well in neither primary energy nor in LCC. The investment costs of renewed CAV system are lower than those of DCV system, but the costs of buying energy are higher due to higher ventilation rates.

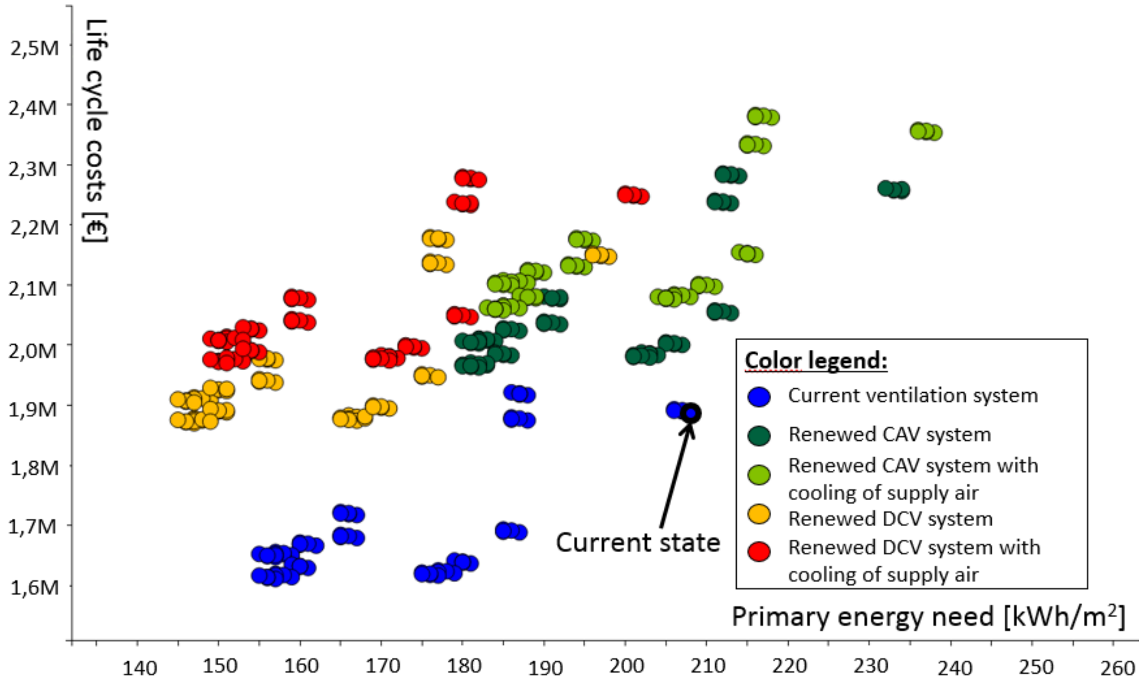


Figure 4.32. All 375 retrofit design alternatives presented in a scatter plot with primary energy need on the x-axis, LCC on the y-axis and color coding by the ventilation system type.

Next, the alternatives were filtered with the requirements that were set previously; primary energy need should be less than 170 kWh/m^{2}a and comfort index should be 90 % or higher. After the filtering, 84 possible alternatives remained, which are presented in Figure 4.33. Only cases that have demand controlled ventilation type (yellow and red) satisfied these both requirements. This figure would indicate that the building does not necessarily require cooling to satisfy the comfort index requirement, since there are also many cases without cooling (yellow). Four promising cases were chosen from the yellow pareto frontier for the next simulation round. However, DCV with cooling does not seem to have significantly higher LCC or primary energy need. Thus, two cases from the red pareto frontier were chosen as well for the next simulation round in order to evaluate in more detail whether the cooling is needed or not. The chosen six cases are highlighted with purple outlines in Figure 4.33. Their input values are presented in Table 4.20 and output values (KPIs) in Table 4.21. The current state of the building was also added to these tables for comparison.

Only retrofit alternatives 1 and 2 have slightly lower LCC than the current state model of the building. However, these costs cannot be directly compared, because in the retrofitted cases the indoor conditions are better. Moreover, based on the condition assessment of the building, the AHUs need to be retrofitted in any case soon. Thus, it would have been one possibility to input zero investment costs for the ventilation system type with the lowest investment costs in order to better see the profitability of more energy efficient solutions. Nevertheless, when all known investment costs are inputted, a better overall picture is obtained. In these six cases, all three window types are represented. In all the cases, the walls are insulated with 200mm of mineral wool. The roof insulation thickness varies from 200mm to 400mm, but it has very little effect on the outputs, as shown previously in the sensitivity analysis.

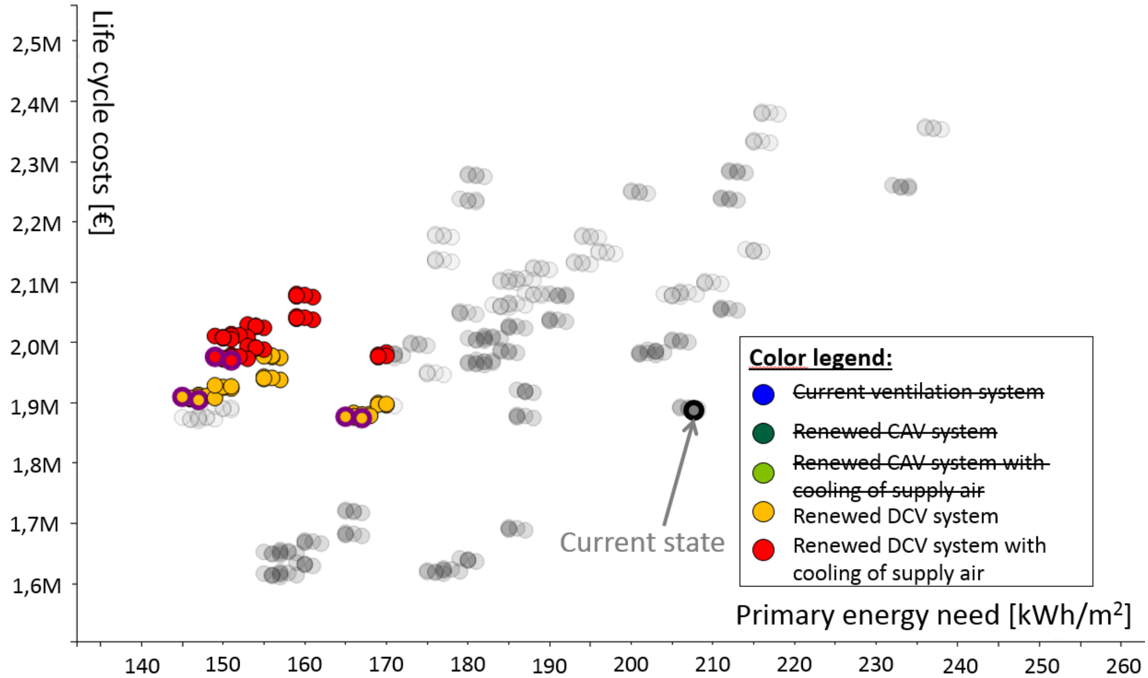


Figure 4.33. Remaining 84 retrofit design alternatives after filtering the results with requirements for primary energy need (<170 kWh/m²a) and for comfort index (>90 %). The six alternatives that were chosen for the next simulation round are highlighted with purple outlines.

Table 4.20. Input values of the chosen six retrofitting alternatives.

Retrofit alternative	Ventilation type	Window U-value [W/(m²·K)]	Window g-value [%]	Wall Insulation thickness [mm]	Wall U-value [W/(m²·K)]	Roof Insulation thickness [mm]	Roof U-value [W/(m²·K)]
1	DCV, no cooling	3,3	48	200	0,14	200	0,19
2	DCV, no cooling	3,3	48	200	0,14	350	0,1
3	DCV, no cooling	0,8	34	200	0,14	200	0,19
4	DCV, no cooling	0,8	34	200	0,14	400	0,09
5	DCV with cooling	1	50	200	0,14	200	0,19
6	DCV with cooling	1	50	200	0,14	400	0,09
Current state	Current	3,3	48	0	0,9	200	0,19

Table 4.21. Output values (KPIs) of the chosen six retrofitting alternatives.

Retrofit alter-native	Energy: Heating energy need [kWh/m²]	Energy: Cooling energy need [kWh/m²]	Energy: Electrical energy need [kWh/m²]	Energy: Primary energy need [kWh/m²]	Emissions: Purchased energy CO_2 [kg CO_2/m²]	Comfort: Comfort index [%]	Costs: LCC [k€]	Costs: Invest-ment cost [k€]	Costs: Energy cost [€/m²]
1	118,8	0	48,7	166	37,2	96	1 874	394	12,3
2	117,1	0	48,7	165	36,6	96	1 877	415	12,2
3	91,3	0	48,7	147	31	95	1 904	635	10,6
4	88,5	0	48,7	145	30,3	95	1 910	661	10,4
5	92,4	2	49,8	151	31,6	96	1 970	670	10,8
6	89,7	2,1	49,8	149	31	96	1 976	696	10,7
Current state	165,1	0	54,2	208	48,4	80	1 888	0	15,7

4.3.3.3 Second retrofit simulation round – uncertainty analysis and determining the best case

The goal of the second retrofit simulation round is to make a decision between the six retrofit alternatives that were chosen in the first simulation round. First, the scenarios for different uncertain parameters are determined. Then, the simulations are performed for the chosen six retrofit alternatives with these different uncertain scenario parameters. The uncertainty analysis results are visualized in the KPA tool, in which the uncertainty analysis section had been implemented at this time. Finally, based on the results, a decision is made between the six retrofitting alternatives.

4.3.3.3.1 Determining the uncertainties

In this work, seven different uncertain parameters were included in the uncertainty analysis: weather, occupancy schedules, people internal load, interest rate, as well as energy price escalation for heating energy and electricity. For each of these parameters, three different possible scenarios were determined, which are summarized in Table 4.22. The values in parentheses are the characteristic values that are used for the sensitivity analysis. Scenario 1 is the base case scenario, which has the same values that were used in the previous simulation run. Scenario 2 and 3 represent two other possible cases within realistic boundaries.

The annual weather in Finland can vary greatly in different years, which clearly has a high impact on the heating energy need. Weather scenario 2 represents a colder year, for which the Finnish standard weather file of weather zone III is used. The average temperature in scenario 2 is 3,4°C, while in the base case scenario it is 5,6°C. Scenario 3 represents a warmer year, with average temperature of 6,8°C. Here, a predicted future scenario for year 2030 was used for scenario 3. This weather file was developed in a study by the Finnish Meteorological Institute, in which they predicted the impacts of climate change [66].

Building usage schedules showed to have high impact on the building energy performance in the first sensitivity analysis results of this thesis (see Section 4.2.4.2). Previously, the AHU operational schedules and all internal load schedules were combined into one parameter for the sensitivity analysis. Now, internal load schedules are parametrized separately. However, there was a bug in the RIUSKA test version, which caused incorrect results if lighting load schedules were parametrized. Thus, it was only possible to parametrize people and equipment load schedules at the time this thesis was being made. Nevertheless, occupancy schedule scenario 2 represents lower utilization, for which the standard schedule from Finnish regulations part D3 [25] was used. Scenario 3 represents higher utilization, in which the base case schedule was modified by increasing the utilization slightly.

Internal heat loads from people [W/m^2] were also chosen for the uncertainty analysis, because no reliable value could be obtained for this parameter during the data collection process. Moreover, the number of people utilizing the building might change during the years. Again, scenario 2 represents lower, and scenario 3 higher people load, with values of $10 W/m^2$ and $18 W/m^2$, respectively.

History has shown that energy prices can change suddenly and unexpectedly, because they are affected by multiple factors. In addition to the balance between supply and demand, also world politics (which can be very unpredictable) greatly affect energy prices. Thus, predicting the future prices of energy is in practice impossible, which makes energy price escalation one of the most significant uncertainty in LCC calculations of building energy efficiency improving investments [67]. Escalation scenario 2, for both district heating and electricity price, is based on calculated values from the Finnish statistics of past three years, during which there has been an unexpected decrease in electricity prices, resulting in negative escalation of -3,3 %. District heating price, however, has still been on the rise during this time period, with escalation value of 1,7 %. However, in RIUSKA the parametrization has to be with equal steps, which is why values -3,0 % and 1,5% were used. Scenario 3 represent a situation in which both energy prices are increasing with the same yearly rate of 3 %. This value is based on a scenario that was used in a study made by Technical Research Centre of Finland [68]. Interest rate was also varied slightly (from 3,0 % to 4,0 %) in order to see how large effect it has on the results. Interest rate depends upon the return requirement of investment, which depends upon the investor. In building energy efficiency investment calculations, the interest rate is usually between 3% and 6% [67]. Here, a relatively low interest rates have been used, because it was assumed that maximum profit is not the main agenda of this retrofit project, since the building is owned by the city.

Table 4.22. Three scenarios for the seven uncertain parameters.

Uncertain parameter	Scenario 1 (base case)	Scenario 2	Scenario 3
Weather (average temperature)	Vantaa TRY 2012 (T_{ave} = 5,6°C)	Jyväskylä TRY2012 (T_{ave} = 3,4°C)	Vantaa TRY2030 (T_{ave} = 6,8°C)
Occupancy schedules (peak hours = hours · utilization rate)[a)]	Current state schedule (1968h)	Low utilization, standard schedule (1252h)	High utilization rate (2448h)
People load [W/m^2]	14	10	18
District heating energy price escalation	0,0 %	1,5 % [b)]	3,0 % [c)]
Electricity price escalation	0,0 %	-3,0 % [b)]	3,0 % [c)]
Interest rate	3,0 %	3,5 %	4,0 %
a) Includes people and equipment schedules.			
b) This escalation scenario is based on calculated escalations from past three years (exceptional decrease in electricity price during 2013 - 2016).			
c) This scenario, in which both energy prices increase, is based on a scenario from [68].			

These uncertainties for the chosen six retrofit alternatives resulted in a total of 13122 simulation cases. Nevertheless, only 486 of these cases require energy calculation, because escalation and interest rate have effect only on the life cycle costs. Therefore, all the 13122 cases were simulated. By simulating all the cases, it was made sure that all the retrofit alternatives have the same uncertain scenarios. With a random sample, there might be a problem that one retrofitting alternative seems better than the others, because the sample did not include the worst case scenarios for that alternative.

4.3.3.3.2 Analyzing results and choosing the optimal alternative

The uncertainties of the three most important KPIs are presented in Figure 4.34 (primary energy need), Figure 4.35 (comfort index), and Figure 4.36 (LCC). In these figures, the range of the KPI values with varying uncertain parameter combinations are presented with red dots. The minimum and maximum values are given in numbers, as well as the average value. On the x-axis are the ID-numbers given for the retrofit alternatives in Table 4.20.

Regarding primary energy need, the average values are slightly higher than in the base scenario (see Table 4.21). The range between minimum and maximum KPI values is the highest for retrofitting alternatives 1 and 2, which both have original windows. Because of original windows, fluctuations in weather have higher effect on the heating energy need, which is the main explanation for their higher range of values. For the other four alternatives, the ranges between minimum and maximum KPI values are slightly narrower. Alternatives 3, 4 and 6 have primary energy need below 170 kWh/m^2 in all scenarios, which was set as one of the requirements for the retrofit.

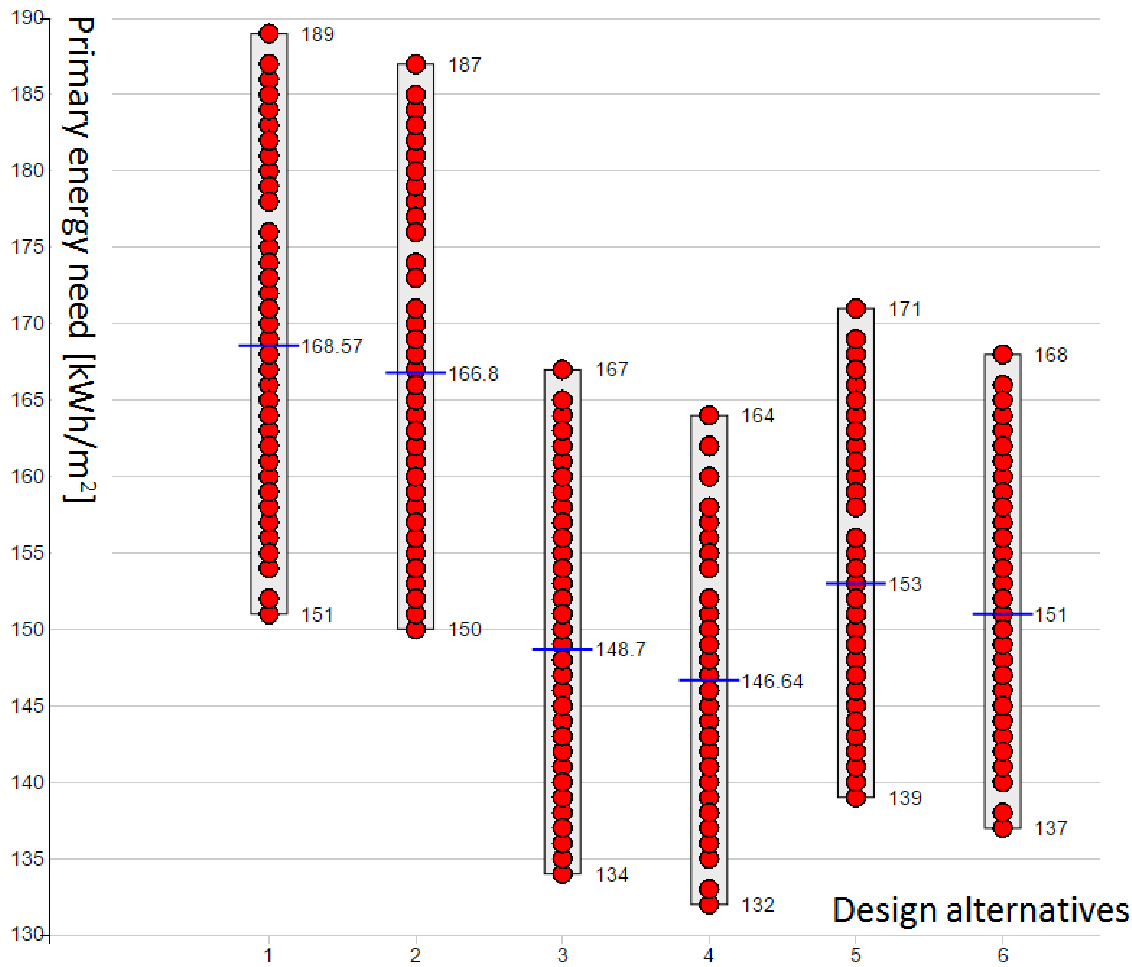


Figure 4.34. Uncertainty visualization of primary energy need.

The uncertainty of comfort index is visualized in Figure 4.35. In this figure, it seems that there are only a few cases for each alternative, even though there are actually 81 different cases for each alternative. The visualization looks like this because RIUSKA rounds the comfort index to the nearest full percentage, and thus there are multiple cases on top of each other in this visualization. Either way, a clear difference can be seen between the alternatives with cooling and the alternatives without cooling. Even though the alternatives without cooling (1 - 4) have excellent comfort indexes in the base case scenario, in many other scenarios they perform more poorly. Alternative 4 proves to be the poorest, with minimum comfort index of 85%, in the scenario with the hottest weather, the highest people load and the highest occupancy schedule. Alternatives 1 and 2, with the original windows, seem to be a bit more stable in terms of comfort index. This is because higher U-value is actually beneficial in the summer, when it is hotter indoors than outdoors. The alternatives 5 and 6 are clearly the most stable, which was expected, since they both have cooling. Even so, the comfort index varies, because the maximum air flows were sized in RIUSKA using the base case scenario. Alternatives 1, 5 and 6 satisfy the requirement of minimum 90 % comfort index in all scenarios. However, alternative 1 has high primary energy need values in too many scenarios. Thus, it can be discarded, leaving alternatives 5 and 6 the most viable options so far.

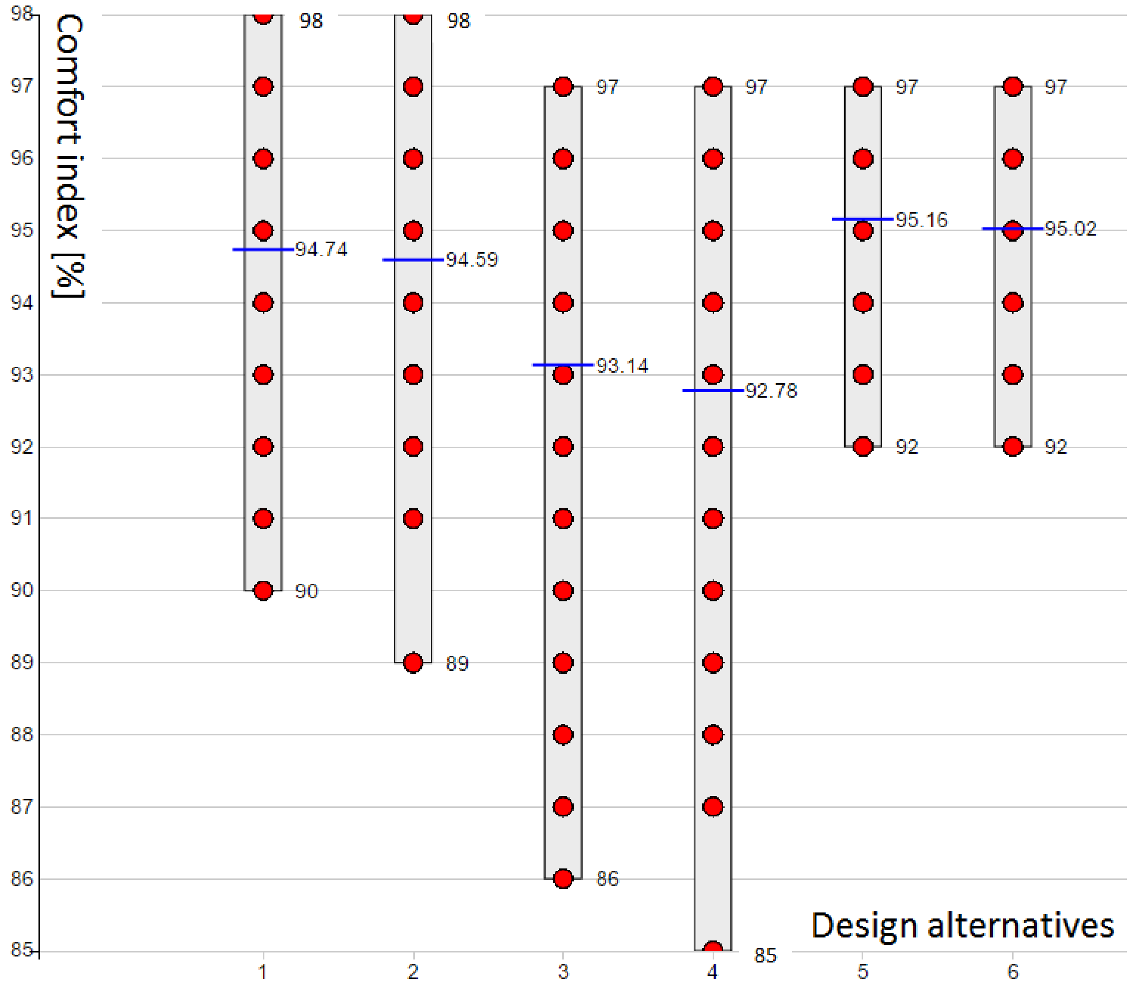


Figure 4.35 Uncertainty visualization of comfort index.

The uncertainty of the third important KPI, LCC, is presented in Figure 4.36. LCC has the highest ranges between minimum and maximum values, which can be explained by the fact that all the uncertain parameters have effect on the LCC. It is important to note that the uncertain inputs are not varied during the 25-year calculation period. For example, the cases with the coldest weather scenario is calculated with that weather file throughout all the years, even though in reality it is unlikely that all years would be equally cold or warm. This causes the uncertainty ranges to be even wider. In addition to weather, also escalation of energy prices has high impact, as is shown later when the sensitivity analysis results are presented. The widest range is for alternative 1, with minimum value of 1,449M€ and maximum value of 2,784M€. For this alternative, the maximum value is as much as 48,6 % higher than in the base case scenario. For the most viable alternatives, 5 and 6, the corresponding percentages are 40,7% and 39,8%, respectively. The average LCC values are very close to each other, as alternative 5 has only 2000 € lower value than alternative 6. However, alternative 5 performs more poorly terms of primary energy need, with maximum value above the required minimum (see Figure 4.34). Therefore, **alternative 6 was chosen as the most optimal choice of these six alternatives.** The official E-value of this alternative was checked with a standard conditions simulation, which resulted in E-value of 158kWh/m^2. Thus, this alternative satisfies the E-value requirement of 173kWh/m^2 (0,8 times the original E-value) given in the Finnish regulations.

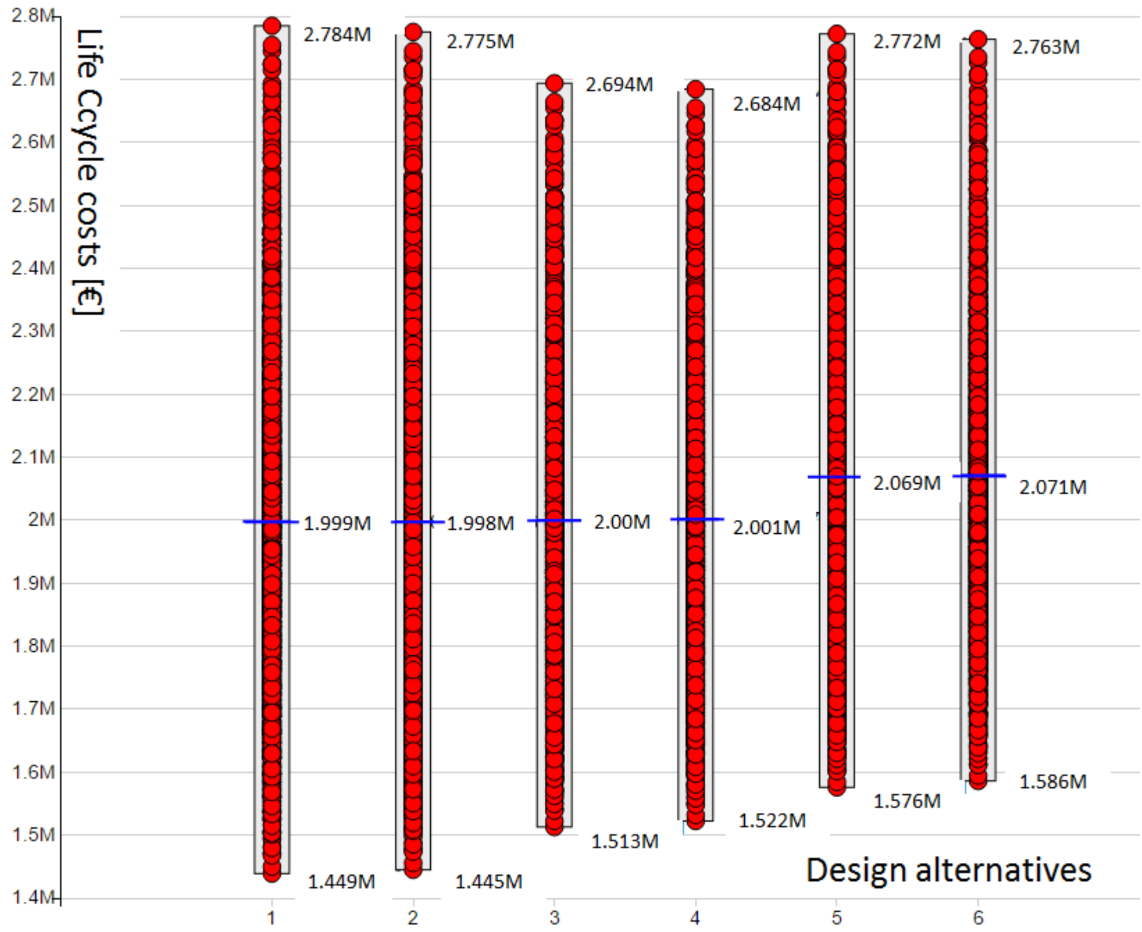


Figure 4.36. Uncertainty visualization of LCC.

To further investigate which parameters have the highest impacts on these uncertainties, also sensitivity analysis results are presented here. These sensitivities are only for the chosen alternative 6. The same simulation results were utilized in the sensitivity analysis.

The sensitivity of primary energy need for the uncertain parameters is presented in Figure 4.37. The corresponding sensitivity of comfort index is presented in Figure 4.38, and of LCC in Figure 4.39. From these graphs can be seen that weather (average outdoor temperature) has a very high impact on all of these KPIs. In addition to being the most significant parameter regarding the sensitivity of primary energy need and comfort index, it also has the third highest SRC value for LCC. Load schedules and people load have the highest effect upon comfort index, and the least effect upon LCC. People load schedules seem to be more influential than equipment load schedules. The economic parameters, escalations and interest rate, naturally only have effect upon LCC. Electricity price escalation is clearly the most significant parameter regarding LCC. Electricity price escalation has higher effect than district heating escalation because of its wider range of possible values, and also because of the higher price of electricity compared to district heating. Weather has rather high impact upon LCC as well, because it greatly affects the heating energy demand, and thus the costs of purchasing energy. Interest rate has a rather low impact, because of the narrow range it was given.

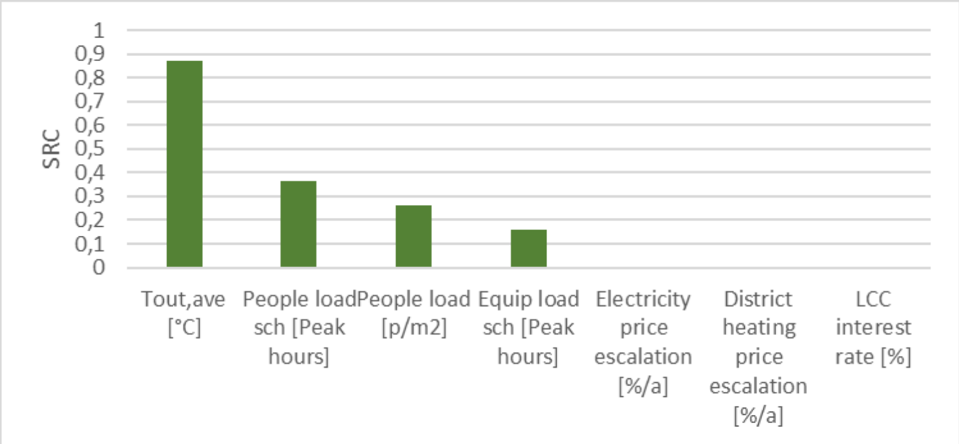


Figure 4.37. Chosen retrofitting alternative - Sensitivity of primary energy need for the uncertain parameters.

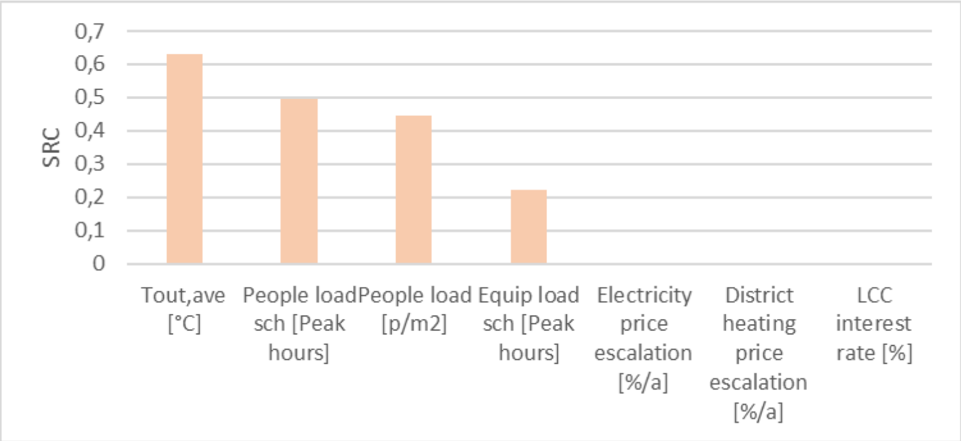


Figure 4.38. Chosen retrofitting alternative - Sensitivity of comfort index for the uncertain parameters.

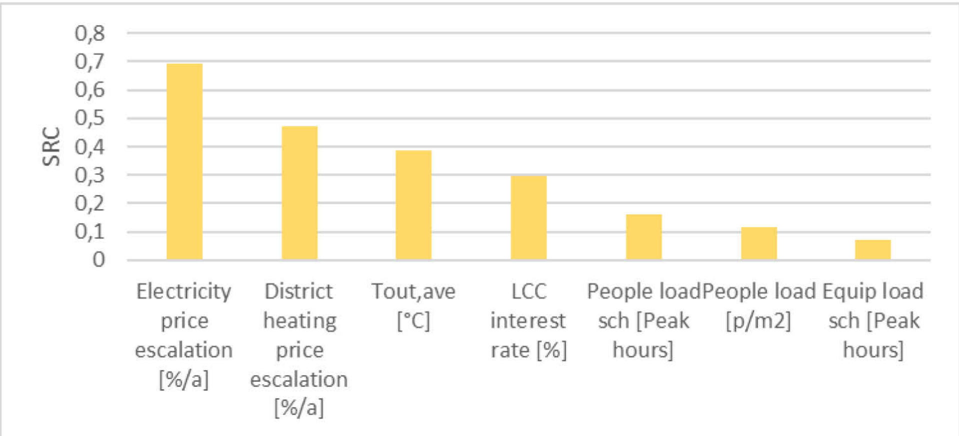


Figure 4.39. Chosen retrofitting alternative - Sensitivity of LCC for the uncertain parameters.

5 Discussion

The discussion in this chapter is mostly based on the experiences gained from the piloting. First, energy modeling of existing buildings will be discussed briefly. This is followed by discussion about the methods and characteristics involved in the process, including BIM utilization, the high number of simulations, the modes of operation, sensitivity and uncertainty analysis, as well as the KPIs. Finally, the further development needs are summarized in the final section.

5.1 Energy modeling of existing buildings

Energy modeling of existing buildings accurately is challenging. Building energy simulations require a large number of input parameters, of which some can never be known accurately. A good example of an uncertain parameter is building occupancy schedules and utilization rates, which affect many things, such as equipment use, lighting use and air demand in DCV systems. Thus, energy modeling of building easily leads to many approximations that can have a significant influence in the simulation results.

The biggest difficulty in energy modeling of existing buildings compared to new buildings, is the challenging task of data collection. Especially regarding very old buildings, the design drawings and documents are likely to be outdated, if found at all. For the pilot building in this work, the architectural drawings were available in CAD format, but only a part of the HVAC and electricity drawings were found. Furthermore, it is often difficult to gather the needed information from the people maintaining the building, since they often do not have enough resources to pay close attention to energy related issues. All this makes it difficult to obtain the needed information without expensive and time consuming audits and measurements. Data collection, however, is a very important task in retrofit projects. All simulation results and recommendations are only as good as the input data used. In the framework of this thesis it was not possible to invest in the data collection as much as it would have been desirable. However, the same problem exists in all retrofit projects, as accurate measurements and investigations can be expensive and time consuming. As shown in this work, it is possible to utilize sensitivity analysis to orient the data collection process and make it more efficient.

Because of the difficulties in collecting the data and defining the input parameters accurately, it is important to calibrate the current state energy models with measured energy consumptions. Even though verifying the model in this way does not guarantee that all the input parameters are correct, it is important that the outputs correlate with the real situation. This allows the comparison of different retrofitting alternatives with rather good reliability, even if the input parameters of the current state energy model have some error. After all, the goal of the process is the comparison of different retrofit design alternatives, not to model the current state of the building. As a conclusion, it is very challenging to simulate and predict the energy use of buildings precisely, but the simulations are an excellent tool in comparing varying design alternatives, and thus can help the decision making considerably.

5.2 BIM utilization

Utilizing BIM in the process has many benefits, but some drawbacks as well. With BIM, it is easier to store and retrieve information during the project, as well as after the retrofitting has been completed. The information stored in the BIM model could be used during the usage period of the building for facility management purposes, and especially beneficial it would be for future retrofit projects. It is important to have knowledge about the renovation history of the building in order to determine the input parameters correctly. In the far future, when BIM is probably used in all building design projects, there would not be problems like this, since all the needed information would be stored in the BIM models.

Another clear benefit of BIM is the more accurate simulation results, since all the rooms and envelope elements can be modeled in their precise locations. Also, utilizing BIM makes the data input faster. The RIUSKA software requires a BIM model to function, and thus BIM utilization was necessary in this work. Without RIUSKA and the parametrized simulation feature, it would have been very difficult to utilize sensitivity and uncertainty analyses, which both require a large number of simulations with varying input parameters.

In this work, the only downside of utilizing BIM was the time required for creating the BIM models. Creation of the models can be time consuming and challenging, especially if the architectural drawings of the building are not available. In this thesis, creating the basic mode models of all the four buildings took approximately one working day, and two more working days for complementing the main building with all the individual rooms and windows. An experienced modeler could probably have done this in less than half the time. However, if architectural drawings are not available, then the situation is more complicated. For this purpose, there are many BIM creation techniques that are currently available, and some that are currently under research. In the future, it might be possible to just walk around the building with a device that automatically creates the BIM model of the building.

Another drawback of BIM utilization is the interoperability issues. This was not a problem in this work, because MagiCAD Room and RIUSKA have been designed to work with each other. However, in actual projects with many different actors, these interoperability issues might cause problems. For example, the architect might use a different software than the HVAC designer, making it difficult to use the same BIM model. Furthermore, the same BIM models cannot be used for all purposes in the design. For example, the model created by the architect cannot usually be used for energy simulation purposes, because it is too complex. This causes more work for the project, because multiple different models have to be created for different purposes.

5.3 The large number of parametrized simulations

The process proposed in this work includes a high amount of parametrized simulations, in which dynamic energy calculation is used. Using dynamic calculation, which takes the time fluctuating phenomena into account, gives more accurate results. However, more accurate results come with the price of demand for higher calculation power and longer calculation times. Nevertheless, this was not seen as a problem in this work. In the basic mode, 1000 simulations took only approximately 1,5 hours of calculation time. In the advanced mode, with individual rooms, comfort index and LCC calculation, the same amount took approximately 2,5 hours. A desktop computer with eight cores was used in these simulations. Moreover, a smaller random sample than 1000 would probably have sufficed as well, which would have decreased the calculation times. Additionally, the setting up of these simulations did not take much time, thanks to the parametrization feature of RIUSKA.

The high number of simulation cases come with many benefits in the process. The sensitivity and uncertainty analyses both require a large number of simulations in order for the results to be reliable, which was the main reason for having such a large number of simulations in this work. In addition, the large number of simulation cases benefit both the creation of the current state energy model, as well as the comparison of different retrofit alternatives. When creating the current state energy model, the large group of simulation cases can be filtered with the obtained information in order to find the case that best represents the actual building. Not only measured consumptions from energy bills can be used for the filtering purpose, but also information obtained about the input parameters. For example, if it is found out that the wall U-value is within a certain range, this knowledge can be used for filtering out the cases outside this range. Regarding the comparison of varying retrofit alternatives, a large number of simulations make it easier to investigate the effect of varying retrofitting measures with a broader view. The more combinations of different retrofit alternatives are taken into account, the more justified decision making.

5.4 The modes of operation

The NewTREND concept divides the retrofitting projects into three modes operation, namely basic, advanced and premium modes. The energy analysis process developed in this work covers only basic and advanced modes, which are used as phases in the process. The premium mode, with the highest requirements in quality of information, would be used for other purposes after the retrofitting has been completed.

The target of the developed process is to introduce energy analysis as a tool that could guide the design process towards energy efficient solutions and support the decision making already from the beginning of the retrofit design project. This is why the energy analysis process was divided into two separate modes of operation. Essentially, the difference between the basic and advanced modes is in the reliability of information that is used as input values for the simulations. In the basic mode, statistical and default values from regulations can be used, while the advanced mode requires more accurate data. At the beginning of retrofit projects, the amount and reliability of information is usually very limited. The basic mode, with very little requirements for information quantity and reliability, can thus easily be utilized already at the beginning of the project. Preliminary energy simulations, with roughly estimated input values, can be used to quickly estimate and compare the energy saving potential of multiple buildings. Another important benefit of the basic mode is the introduction of sensitivity analysis for supporting the challenging data collection task needed in retrofit projects. The main drawback of the basic mode is the inaccuracy of the results, which is caused by the assumptions in the input parameters. This causes a risk that the results might guide the design in the wrong direction. Therefore, the results of the basic mode should be analyzed with criticism. Moreover, even though creating the basic mode BIM models and performing the simulations is rather easy, it still requires some efforts and time. Therefore, it might be argued if it would be better to use advanced mode already from the beginning of the project. This could be true for a project where all relevant input parameters are already known and the building is going to be retrofitted in any case. Nevertheless, usually the situation in retrofit projects is that very little information of the building is known at the beginning of the project. In this case, it is easier to start the energy analysis process with the basic mode in order to allow the utilization of early energy simulations and the sensitivity analysis to guide the data collection task.

In the advanced mode, a more reliable current state energy model of the building is created, which is needed as a base case for comparing the different retrofitting alternatives. This mode supports the actual retrofit design the most by simulating as many possible retrofit alternatives as possible and comparing them to each other. If needed, the simulations can be made in multiple iteration rounds, while utilizing sensitivity analysis results in choosing the alternatives for each round. In order to make more justified decisions about the design, also uncertainty analysis is included in the advanced mode as a part of the process. Thus, the most important benefits of the advanced mode are the more accurate energy simulations as well as the additional support gained from the sensitivity and uncertainty analyses. However, compared to the basic mode, the advanced mode requires much more efforts and time. Moreover, it is possible that the advanced mode part of the process is difficult to assimilate, and the energy analyst needs to be familiar with sensitivity and uncertainty analyses in order to benefit from this process.

The creation of the advanced mode BIM model took more time than creating all four basic mode BIM models. Thus, it seems beneficial to first perform rough preliminary simulations in the basic mode, before taking the time to create the more detailed advanced mode BIM model. This way, preliminary energy performance can quickly be estimated already at the beginning of the project. If retrofitting the building does not seem beneficial based on the basic mode results, or for some reason it is decided that further simulations are not needed, the time required for creating the more detailed BIM model can be saved.

The modes of operation are based on two different specifications: level of development by American Institute of Architects and level of detail by CityGML. However, during the writing of this thesis, it was noticed that these specifications are rather complicated and vague. Moreover, in different retrofit projects, not always the same amount of information is available. Thus, in some projects, there would be no point in trying to get all the information that these specifications require for each mode of operation. Therefore, more focus should be put into analyzing the sensitivity analysis results, rather than studying the LOD specifications and what they would require. Nevertheless, regarding the process developed in this thesis, these specifications offer some guidelines and make it easier to define the modes of operation. Inclusion of simple LOD tables to the process could be considered as further improvement outside this thesis. In these tables, it would be marked which AIA’s LOD level each input parameter represents in order to inform the design team how reliable each used parameter is. Also the source of the information would be important to document.

In the piloting part of this work, the simulated current state energy consumptions were very close to each other in the basic and the advanced mode, even though there were many differences in the input parameters. This is partly explained by the fact that both models were calibrated with measured energy consumption data. However, yearly data was used in the basic mode, whereas monthly data was used in the advanced mode. The difference could also have been much higher, for example if a different case had been chosen in the basic mode. The similarity in the simulated energy consumptions was mostly like just a coincidence. Therefore, it should always be remembered, that even if the simulated consumptions match the measured consumptions very well, it is not guaranteed that the model is accurate, i.e. that the input values are correctly defined.

5.5 Sensitivity and uncertainty analyses

In the process, sensitivity analysis is used for three different purposes: (1) to guide the data collection task, (2) evaluate which individual retrofitting measures have the highest impact upon the building energy performance and (3) to support the uncertainty analysis by identifying the parameters that are the most responsible for the uncertainties. Uncertainty analysis, on the other hand, is only used in the final stage of the process in order to make a well justified decision between the most promising retrofitting alternatives.

The first, and probably the most useful of these three purposes for sensitivity analysis, is the use of sensitivity analysis to guide the data collection task. The sensitivity analysis is used to identify the most important parameters, of which accurate information is required. With it, the parameters that have very little significance can also be identified, for which default values from regulations or statistics can be used. This helps to focus efforts in collecting data about the most important parameters, making the data collecting task more efficient and saving valuable time in the process. In the piloting part of this thesis, this kind of sensitivity analysis was done both in the basic mode and later in the advanced mode. The basic mode results gave a good overall picture about the relative importance of the parameters. However, a seasoned energy analyst probably could rather easily have predicted that which are the most significant parameters affecting the energy performance of the building. Some parameters, such as airflow rate, building schedules and HRU efficiency are well known to be influential parameters. Nevertheless, this kind of sensitivity analysis gives more concrete results about the relative importance of the parameters, and the results can be used to justify which parameters need to be known more accurately. Furthermore, if the pilot building had more complicated HVAC systems, such as cooling, the sensitivity results would have been harder to predict. After all, every building is at least slightly different from each other, making it difficult to estimate the relative importance of the input parameters based only on experience from previous projects. In addition, it needs to be mentioned that the benefits of this kind of sensitivity analysis is not restricted only to the guiding of data collection. After the data has been collected, the already simulated cases can be further utilized by filtering them to find the case that best represents the current state of the building. Therefore, additional simulations are not necessarily needed, even if all the data is not acquired. This kind of filtering proved to be very useful in examining the possible values of the parameters for which accurate information could not be obtained.

If the data collection is carried out in multiple stages, as it was done in the piloting part of this thesis, a second sensitivity analysis simulation round for the purpose of data collection can be performed, after obtaining some of the needed information. The idea of the second round is to get a better picture about the data that is still missing, by dropping out the already known parameters and the parameters that proved to be insignificant, as well as by narrowing down the ranges of the still unknown parameters. For example, in the piloting part of this thesis, the range of the wall U-value was narrowed from 0,70 - 1,00 W/m^2K to 0,90 - 1,00 W/m^2K, based on the structure information obtained from the condition assessment. With this new range, the wall U-value showed lower significance, and thus it was decided that there is no need for a more accurate estimate. However, the usefulness of the second round was not as high as the usefulness of the first round. The necessity of the second round essentially depends upon the projects and how the data is collected. Thus, it should be considered in each project, whether it is needed or not. Nevertheless, with the parametrization feature in RIUSKA, this does not take too much time.

The second purpose, for which sensitivity analysis is utilized in the process, is to evaluate which individual retrofitting measures would have the highest impact upon the building energy performance. For this purpose, the weighted sensitivity analysis visualization can be utilized. With the weighted sensitivity, it is possible to take into account the preferences of the decision maker and show only one graph instead of many. This kind of graphs would probably prove to be the most useful in showing the client (owner of the building) what retrofitting actions have the highest overall effect. After all, the client usually is not an energy expert, and thus showing only one graph might be much less confusing than showing multiple graphs. This kind of sensitivity analysis results can also be of benefit for the actual design team, especially in the case that the number of different retrofitting combinations is very high. Then, only a small random sample of the whole combination group can be simulated first for the sensitivity analysis purpose, after which the group could be narrowed down based on the sensitivity analysis results. In this work, however, this was not needed, and the same retrofit design alternative would have been chosen regardless of the sensitivity analysis results.

The third purpose of sensitivity analysis is to support the uncertainty analysis by identifying the parameters that are the most responsible for the uncertainties. It is always good practice to analyze also sensitivity when performing uncertainty analysis. By identifying the factors that are the most responsible in causing the uncertainties, it can be considered if something can be done to mitigate these uncertainties. In the piloting part of this work, weather proved to be causing the most uncertainty regarding the primary energy need of the building, and correspondingly electricity price escalation regarding the life cycle costs of the building. Both of these uncertain parameters are uncontrollable by the user, and thus they just need to be accepted and taken into account in decision making. On the other hand, some other parameters, such as internal loads and their schedules, can in certain limits be controlled with building design and management. In addition, even though some parameters (such as weather and energy price escalation) cannot be influenced directly, sensitivity analysis can be used to compare the sensitivities of different retrofit alternatives to these uncontrollable parameters. Thus, this kind of sensitivity analysis can provide some concrete and usable information, in addition to just identifying the most influential uncertain parameters.

In addition, it needs to be mentioned that sensitivity analysis can only be performed for numerical values. However, in building design the design options usually do not have just one characteristic value, and thus it is not always obvious that which value is inputted in the regression equation. For example, windows can be characterized by their U-value or g-value. Also, a wall type can be characterized by its U-value or by its heat capacity. It is possible to use only one of these values, as was done for the wall type in this work. The second option is to analyze the sensitivity to both values separately, as was the procedure for windows in this thesis. The third option is to create a combined characteristic value, which was tested for the ventilation system type in this thesis. If only one value is used, then it is possible that the results are misleading, because the sensitivity is analyzed only from one perspective. On the other hand, if the values are inputted separately, it can lead to combinations that do not exist in reality. Also, creating a combined characteristic value has the risk of misleading results, if the value is determined poorly.

The utilization of uncertainty analysis in the process proved to be useful, since it made it easier to make a decision between the six cases that were chosen for the second simulation run. Before the uncertainty analysis, it seemed that the building would not require cooling because the comfort indexes were almost as good for the alternatives without cooling as they were for the alternatives with cooling. However, with the uncertainty analysis, it was noted that for the cases without cooling, there are multiple possible scenarios in which the comfort index requirement is not satisfied. Thus, a design alternative with cooling was chosen.

A simple scatter plot showing the uncertainty range was chosen for the visualization of uncertainty in this work, because of multiple reasons. It was simple to implement in the KPA tool, easy to understand and it allows easy visualization and comparison of multiple alternatives at the same time. However, it is possible that this visualization does not provide enough information for the decision maker. In this work, the uncertainty ranges were quite similar in each case regarding some KPIs, and thus it would have been beneficial to have also more specific information about the dispersion of the cases. The most information about the dispersion, and about the probability of a value in some certain range, could be provided by implementing PDFs and ECDFs, which were described in Section 2.3.5. The problem is, however, that for these visualizations it would be best to have continuous probability distributions for the input parameters. Easiest way would be to assume that each case has the same probability (as was done in this work), or that the cases are normally distributed, but both options can lead to misleading results. Justifiably determining the probability distributions can be very challenging. Another way to provide information about the dispersion of the cases in this kind of analysis would be to include histograms in the visualization, alongside with the scatter plots. They do not provide as much information, but would still give some idea about the dispersion. For example, histograms could be used to visualize how many of the cases are outside the required boundaries. This can roughly be seen from the scatter plot as well, but it would be much easier to see from histograms. The problem with histograms, however, is that it is harder to visualize multiple design alternatives with it. Therefore, the box plot might be the best choice for this kind of uncertainty analysis. The box plot allows easy comparison of multiple retrofit alternatives simultaneously, while at the same time providing information about the dispersion. Also, the "requirement setup" section in the KPA tool should be utilized in the visualization of the uncertainties. The requirements set by the user should be shown in the visualization, for easier interpretation of the results.

The biggest challenge of sensitivity and uncertainty analysis in building energy simulations is defining the input parameter ranges correctly to correspond the real situation. The wider the range is, the more sensitive will the model appear to be for that parameter. This was very well perceived during the simulations of this work as well. Therefore, it is very important to define the ranges carefully within realistic boundaries and avoid defining the ranges too wide or too narrow. Utilizing normal distributions for the input parameters might offer more reliable sensitivity and uncertainty analysis results, but then the problem would be in defining the standard deviations and averages for these distributions. Nevertheless, it might be worth it to investigate if normal distributions could be used for some parameters in the parametrization feature of RIUSKA. This would require creating a database for averages and standard deviations of different input variables categorized by building type and age. Another issue (regarding especially sensitivity analysis for data collection) that needs to be mentioned is, that not all the needed information can be parametrized. For example, in the advanced mode simulations, room specific information as well as the service areas of the AHUs are needed, which cannot easily be parametrized. Therefore, the energy analyst should always consider which parameters are important outside the sensitivity analysis as well.

5.6 Key performance indicators and cost data

Primary energy need, comfort index and LCC were used as the primary KPIs in this work, based on which the retrofit alternative was chosen. Thus, all three main aspects in building design were taken into account: energy, comfort and costs. Primary energy need includes the environmental aspect as well, because it multiplies the energy carriers with their specified weighing factors. Also, the less energy is consumed, the less emissions are generated. Therefore, it was not seen necessary to analyze CO_2 emissions separately.

Comfort related KPIs, such as temperature constancy and CO_2 concentration, are very important in building design, as the target is always to design buildings that offer a healthy and comfortable environment for its inhabitants. In this work, because of RIUSKA's restrictions, only one temperature related KPI, comfort index, was able to be used. However, this index does not take into account the quality of indoor air, as it is based only on temperature constancy in the building. Because of this, the simulated difference in comfort was not that big between the current ventilation system and the renewed systems. The inclusion of some other KPI that would take into account the impurities in the indoor air, would be a valuable addition to the process.

Life cycle costs (LCC) was seen as the most important cost related KPI in this work, since it includes all the costs in the selected calculation time. However, projects always have some budget for the investment, which cannot easily be exceeded. Thus, total investment cost is an important KPI as well. With the KPA tool, it is easy to filter out the alternatives that exceed the predetermined budget. The biggest challenge for the LCC calculation is obtaining reliable cost data. The required cost data for LCC calculation include investment, renewal, repair and energy costs.

Including cost analysis in this kind of process has basically three options. The first option, that was used in this work, is to manually input cost data into the software for each retrofitting alternative that is simulated. This kind of procedure, however, can be rather time consuming if the number of design alternatives is high. Furthermore, even roughly estimating the costs of different retrofitting alternatives can be challenging. The second option would be to implement automatic cost functions that calculate the investment, repair and renewal costs of each design solution based on some default cost data base. For example, the investment costs of adding insulation to the wall would automatically be calculated based on the type of the wall, type of the insulation material and thickness of the insulation. Automating this task could save a significant amount of the user's time. However, the problem is that the investment costs (and other costs as well) can be very different in each project. Thus, automatic cost data would include the risk of producing inaccurate results, which could guide the design process in the wrong direction. The third option would be to focus only in the energy efficiency related KPIs in the parametrized simulations, and then perform cost analysis separately for some of the most promising cases. This would allow more time and resources to be spent on determining the costs for the selected smaller group of cases, which would produce more reliable results. On the other hand, it is very problematic to compare design alternatives only based on energy performance KPIs, because they are strongly dependent upon each other and the changes caused to them by varying input parameters are mostly parallel. For example, when heat energy consumption decreases, also primary energy need and emissions decrease. If costs are not included in the process, then most likely the most expensive alternatives are chosen, for example massive insulation, windows with the best U-value and roof full of solar panels. This kind of alternatives, however, are not likely to be economically feasible, and cost related KPIs are usually the most important for the client. In order for the large number of simulations and their visualization to have the most benefit, there should be KPIs between which compromises have to be made. As a conclusion, the best way could be to combine these three options. First, a rough, automated or user inputted cost data is included in the large group of parametrized simulations. This could be automated for the retrofitting alternatives that usually have approximately the same costs in different kinds of projects. For example, the price of renewing or sealing windows is probably quite the same (per window area) in all projects. Then, a smaller group of promising design alternatives are chosen, and an LCC expert calculates more accurate cost estimation for these alternatives.

5.7 Further development needs

The work that was carried out in this thesis is not yet finished. The topic proved to be wide, and thus some shortcuts had to be made. Some of the further improvement needs were covered in the previous sections of this chapter. They are summarized in this section, and a few more suggestions are added.

First of all, the process should go through further testing and fine tuning in multiple test projects, while comparing it to the traditional way of doing energy analysis. The benefits and disadvantages of each part of the process could then be better evaluated, and some parts might be modified or left out.

In order to make the process more efficient, a few databases would be useful. The most useful database would include typical input parameter ranges for buildings of different types and construction years. This database should be based on national statistics. It should include typical values for the envelope components (typical construction types, U-values, infiltration rates etc.) and HVAC systems (typical system types, HRU efficiencies, SFP values etc.). It could also be investigated if normal distributions could be determined for some input parameters. Internal loads and schedules could be left out, since standard values can easily be found from the regulations and it would be impossible to create schedules that apply to all buildings. If possible, this database could be integrated into RIUSKA, so that by choosing the building type and construction year, the software would automatically suggest ranges for the input parameters. These ranges could then be used for the sensitivity analysis simulations, which would save considerable amount of time. Another database could be created for the typical uncertainty scenarios that are mostly the same in all projects, such as escalation rates and weather. If the same scenarios for these parameters would be used in all projects, the results would also be better comparable across varying projects. A third useful database would be for cost data, that would include typical investment, repair and renewal costs for different retrofitting alternatives.

A more informative uncertainty analysis visualization would also be a beneficial addition to the process. Currently, the KPA tool shows only the average, as well as the minimum and maximum value between which the values are located. It would be beneficial to have better knowledge about the dispersion of the cases as well, which could be done by implementing box plots or histograms in the visualization.

Some improvements can be suggested for the RIUSKA software as well, based on the experience gained from this work. One important improvement would be the implementation of renewable energy generation, such as solar panels, wind turbines and heat pumps. Additionally, more HVAC related parameters could be added for the parametrization feature of RIUSKA, such as average air flow, domestic hot water usage and the efficiency of the heat distribution system. Another good feature would be to be able to bind a certain infiltration rate to a certain window type, because the tightness of windows usually has a high impact upon the infiltration rate of the building. Currently, it is only possible to parametrize these two separately. Additionally, integrated solutions for neighborhoods could not be analyzed in this thesis, because in RIUSKA it is only possible to work with one building at a time. If it would be possible to simulate multiple buildings simultaneously, the energy performance of a neighborhood could be better evaluated as a whole. For example, it would allow to evaluate whether it would be better to fully retrofit one building or make smaller changes to all buildings. In addition, the synergies of shared energy systems could be better evaluated, and the shading caused by the other buildings could be taken into account in the simulations. Also, implementation of a KPI that would take the impurities of indoor air (especially CO_2) into account would be beneficial. However, implementation of such a KPI would probably require a high amount of work.

Regarding the utilization of BIM, further investigations are needed about how could the energy simulation BIM models be further utilized in the other parts of the design. Additionally, a natural continuation for this work would be to develop a process for the post-construction phases of buildings, which would utilize the premium operational mode.

6 Summary and conclusions

The objective of this thesis was to extend and improve a process for energy analysis in neighborhood-scale retrofit projects. Because the process will be used to support multi-criteria decision-making in retrofit projects, it should take into account various factors, such as energy efficiency, comfort, as well as economic and environmental aspects. However, these factors can conflict with each other, making this an optimization task. This new process utilizes several advanced methods, namely BIM, dynamic energy simulations, as well as sensitivity and uncertainty analyses. In addition to these methods, the process has two other important features. These are the division of the process into two operational modes, the basic and advanced mode, as well as the large number of parametrized simulations performed in both modes. The process was tested in a real pilot neighborhood, which will in reality be retrofitted in the coming years. Based on the piloting, the thesis evaluated the benefits and drawbacks of the different elements and methods used in the process.

The modes of operation are used as phases in the process. They differ from each other in their requirements for information reliability and in the level of geometrical detail required from the BIM models. The basic mode utilizes simple BIM models without interior features, which makes the creation of the models faster. In addition, since the basic mode uses default values from regulations and building statistics, it is possible to perform energy simulations already in the initial phases of the project. These preliminary energy simulations, based on roughly estimated input values, can be used to quickly estimate and compare the energy-saving potential of multiple buildings in a neighborhood. Another important benefit of the basic mode is its ability to utilize sensitivity analysis for supporting the challenging data collection task needed in retrofit projects. The main drawback of the basic mode is the inaccuracy of the results, which is caused by the assumptions in the input parameters. If the simulation results in the basic mode appear promising, the process moves forward to the advanced mode. If retrofitting the building does not seem feasible, or for some other reason it is decided that further simulations are not needed, the time required for creating the more detailed advanced mode BIM model can be saved.

The goal of the advanced mode is to discover the best possible retrofit design solution. The advanced mode requires that the BIM model is complemented with individual rooms and windows in their precise locations. With this more detailed BIM model and the collected information concerning the building, a more reliable current state energy model can be created for the building, which is then used as a base case for comparing the various retrofit design solutions. If needed, the retrofit simulations can be made in multiple iteration rounds, while utilizing sensitivity analysis results in choosing the alternatives for each round. The weighted sensitivity analysis visualization method can be used to make the interpretation of the results easier while taking the preferences of the decision maker into account. In order to make more justified decisions, an uncertainty analysis is also included in the final phase of the advanced mode as an important part of the process. The most important benefits of the advanced mode are the more accurate energy simulations as well as the additional support gained from the sensitivity and uncertainty analyses. However, compared to the basic mode, the advanced mode requires much more efforts and time.

Utilizing BIM makes it is easier to store and retrieve information during the project, as well as after completing the retrofitting project. Another clear benefit of utilizing BIM is the more accurate simulation results, since all the rooms and envelope elements can be modeled in their precise locations. In this work, the only disadvantage of utilizing BIM was the time required for creating the BIM models. Nevertheless, this was not seen as a problem in this work, since the availability of architectural drawings allowed the BIM models to be rapidly created. The software used in this work showed no interoperability problems with BIM, even though it has been reported as an issue in the literature.

The sensitivity and uncertainty analyses require a large number of simulations to ensure that the results are reliable, which was the main reason for including such high number of parametrized simulations in the process. In addition, the large number of simulation cases benefit not only the creation of the current state energy model, but also the comparison of different retrofitting alternatives. However, one disadvantage is that a higher number of simulations leads to a higher demand for calculation power and time. Nevertheless, this did not prove to be problematic in this work, since the calculation times remained reasonable.

The sensitivity analysis proved to be a versatile tool in the energy analysis process, as it is used for three different purposes: (1) to guide the data collection task, (2) to determine which individual retrofitting measures would have the highest impact on the building energy performance and (3) to support the uncertainty analysis by identifying the parameters that are the most responsible for any uncertainties. Thus, the sensitivity analysis can be used to guide the design process and decision making at various stages in the design process. In the piloting of the process, using the sensitivity analysis to guide the data collection proved to be the most useful of these three purposes. However, the situation might differ in other projects.

The uncertainty analysis is only used in the final stage of the process in order to make a well justified decision between the most promising retrofitting alternatives. The uncertainty analysis proved to be useful in the piloting, since it made it easier to make the final decision between the most promising retrofit design alternatives. It would be important to include uncertainty analysis in the design of buildings, since the uncertain scenario parameters, such as weather and escalations rates, can have significant effects on the energy performance and life cycle costs of buildings. However, deficiencies were detected in the visualization method used for the uncertainty analysis. The current visualization used in the KPA tool does not necessarily provide enough information about the dispersion of the results. Thus, it should be considered whether more advanced visualization methods, such as histograms or box plots could be implemented in the visualization tool.

The greatest challenge in using sensitivity and uncertainty analyses is to correctly define the input parameter ranges in order to correspond to the real situation. The wider the range is, the more sensitive the model will appear to be for that parameter, thus making the defining of the ranges the most critical part in performing both analyses. Therefore, it is very important to define the ranges with care and to avoid defining the ranges too wide or narrow. In this work, discrete values with equal probability were used for the parametrization. However, some sources claim that it would be best to use normal probability distributions for the input parameters [47]. This might offer more reliable results, but then the problem would be in defining the standard deviations and averages for these distributions.

In order to make the process more easily adaptable and effective, some future development is required. Firstly, the process should go through further testing and evaluation in other projects. In addition, creation of more databases would be very useful in order to make the process easier and faster to use. One of these databases would contain typical values for the building envelope components and HVAC systems, categorized by building type and construction year, which could be used in determining the input parameter ranges for the sensitivity analysis. Another database could be created for typical scenarios involving uncertain parameters, such as escalation rates and weather. A third useful database would include typical cost data for different retrofit solutions, which could be used for roughly estimating costs in all the projects. Having these databases integrated into the simulation software would make it much easier and faster to go through the process. Additionally, a natural continuation for this work would be to develop a process for the post-construction phases of buildings, which would utilize the premium operational mode. It would also be important to investigate how the BIM models created in this process could be further utilized in the other disciplines of design.

As a general conclusion, the process proposed in this thesis shows promise, though it still requires further testing, fine-tuning and improvements. The implementation of such an energy analysis process into the design of building retrofits could provide a step towards a more efficient way of utilizing energy simulations. With the proposed process, energy simulations could be used to guide the design process even at the initial phases of the project in order to effectively support decision making throughout the project.

References

1. European Commission. Buildings. [Online publication]. 2016. [Referred 16.03.2016]. Available from: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

2. McNeise, A. Building Retrofits Critical to Europe's Low-Carbon Pathway. Bresaer. [Online publication]. 2015. [Referred 16.03.2016]. Available from: http://www.bresaer.eu/building-retrofits-critical-to-europes-low-carbon-pathway/

3. Ympäristöministeriö. Uudet Rakentamisen Energiamääräykset Annettu. [Online publication]. 2011. [Referred 16.03.2016]. Available from: http://www.ym.fi/fi-FI/Ajankohtaista/Tiedotteet/Tiedotteet_2011/Uudet_rakentamisen_energiamaaraykset_ann(900)

4. Ympäristöministeriö. Ympäristöminiterion asetus rakennusten energiatehokkuuden parantamisesta korjaus- ja muutostöissä. [Online publication] 2013. [Referred 17.03.2016] Available from: http://www.ym.fi/fi-FI/Maankaytto_ja_rakentaminen/Energiatehokkuus_huomioon_luvanvaraisess(3871)

5. Ma, Z., Cooper, P., Daly, D. and Ledo, L. Existing Building Retrofits: Methodology and State-of-the-Art. Energy and Buildings, 2012. Vol. 55. pp. 889-902. ISSN 0378-7788.

6. Renovate Europe. Ambition and Objectives. [Online publication]. [Referred 26.04.2016]. Available from: http://renovate-europe.eu/the-campaign/ambition-objectives

7. Naaranoja, M. and Uden, L. Major Problems in Renovation Projects in Finland. Building and Environment, 2007. Vol. 42, no. 2. pp. 852-859. ISSN 0360-1323.

8. Clarke, J. Energy Simulation in Building Design. Second Edition. Oxford, Butterworth-Heinemann, 2001. Preface, pp. ix-x. ISBN 9780750650823.

9. Schlueter, A. and Thesseling, F. Building Information Model Based Energy/Exergy Performance Assessment in Early Design Stages. Automation in Construction, 2009. Vol. 18, no. 2. pp. 153-163. ISSN 0926-5805.

10. Mumovic, D. and Santamouris, M. A Handbook of Sustainable Building Design & Engineering. Earthscan, 2009. ISBN 978-1-84407-596-6.

11. Laine, T., Bäckström, K. and Järvinen, T. Common BIM Requirements 2012, Series 10: Energy Analysis. [Online publication]. 2012. [Referred 19.04.2016]. Available from: http://www.en.buildingsmart.kotisivukone.com/3

12. Laine, T. and Karola, A. Benefits of Building Information Models in Energy Analysis. Olof Granlund Oy, Helsinki, Finland. [Online publication]. 2007. [Referred 20.04.2016]. Available from: https://www.irbnet.de/daten/iconda/CIB8170.pdf

13. Idman, T. Energiasimuloinnin parametrisointi ja rakennuksen energiatehokkaan suunnitteluratkaisun tuottamisen, analysoinnin ja päätöksenteon kehitysperusteet. (Parametrization of energy simulation and development of energy-efficient building design analysis and decision making process). Master’s thesis. Aalto University School of Engineering, Department of Energy Technology. Espoo, Finland. 2013.

14. Henttinen, T. Common BIM Requirements 2012, Series 1: General Part. [Online publication]. 2012. [Referred 20.04.2016]. Available from: http://www.en.buildingsmart.kotisivukone.com/3

15. Volk, R., Stengel, J. and Schultmann, F. Building Information Modeling (BIM) for Existing Buildings — Literature Review and Future Needs. Automation in Construction, 2014. Vol. 38. pp. 109-127. ISSN 0926-5805.

16. Tian, W. A Review of Sensitivity Analysis Methods in Building Energy Analysis. Renewable and Sustainable Energy Reviews, 2013. Vol. 20. pp. 411-419. ISSN 1364-0321.

17. Stjelja, D. Advanced energy analysis method for optimal building retrofit design. Master's thesis. University of Zagreb, Faculty of mechanical engineering and naval architecture. Zagreb, Croatia. 2016.

18. Penttilä, H., Nissinen, S. and Niemioja, S. Tuotemallintaminen Rakennushankkeessa. Rakennusteollisuus RT ry, Rakennustietosäätiö RST, 2006. 64 p. ISBN 978-951-682-796-7.

19. ISO 29481-1:2010. Building Information Modelling -- Information Delivery Manual -- Part 1: Methodology and Format. [Online document]. International Organization for Standardization, 2010. 28 p. [Referred 25.04.2016]. Available from: http://www.iso.org/iso/catalogue_detail.htm?csnumber=60553

20. National BIM Standard - United States. Frequently Asked Questions about the National BIM Standard - United StatesTM. [Online publication]. [Referred 16.03.2016]. Available from: https://www.nationalbimstandard.org/faqs

21. Wijayakumar, M. and Jayasena, H.S. Automation of BIM Quantity Take-Off to Suit QS's Requirements. [Online document] The Second World Construction Symposium 2013: Socio-Economic Sustainability in Construction, 2013. pp. 70-80. [Referred 15.05.2016]. Available from: http://www.academia.edu/3719630/AUTOMATION_OF_BIM_QUANTITY_TAKE-OFF_TO_SUIT_QSS_REQUIREMENTS

22. Micro Aided Design. ArchiCAD-Tuotemallintamisohje. [Online document] 2009. [Referred 06.05.2016]. Available from: http://www.mad.fi/tiedostot/pdf/kasikirja10/TM.pdf

23. Henttinen, T. Common BIM Requirements 2012, Series 3: Architectural Design. [Online publication]. 2012. [Referred 19.04.2016]. Available from: http://www.en.buildingsmart.kotisivukone.com/3

24. Graphisoft. IFC-Based Data Exchange - Frequently Asked Questions. [Online publication]. [Referred 26.05.2016] Available from: https://www.graphisoft.com/downloads/addons/ifc/FAQ/index.html#1

25. Ympäristöministeriö. Suomen Rakentamismääräyskokoelma D3: Rakennusten Energiatehokkuus. [Online document]. 2012. [Referred 15.05.2016]. Available from: http://www.finlex.fi/data/normit/37188-D3-2012_Suomi.pdf

26. BuildingSMART. Coordination View Version 2.0 Summary. [Online publication]. [Referred 05.04.2016]. Available from: http://www.buildingsmart-tech.org/specifications/ifc-view-definition/coordination-view-v2.0

27. BuildingSMART. Space Boundary Summary. [Online publication]. [Referred 05.04.2016]. Available from: http://www.buildingsmart-tech.org/specifications/ifc-view-definition/space-boundary-addon-view

28. Weise, M., Liebich, T., See, R., Bazjanac, V., Laine, T. and Welle, B. Implementation Guide: Space Boundaries for Energy Analysis. [Online document] Open Geospatial Consortium (OGC), 2011. [Referred 05.04.2016]. Available from: http://www.blis-project.org/IAI-MVD/documents/Space_Boundaries_for_Energy_Analysis_v1.pdf

29. Palomäki, J., Olenius, A. and Nissinen, S. Korjaustöiden Laatu 2011. Talonrakennusteollisuus ry ja Rakennustietosäätiö RTS, 2010. 217 p. ISBN 978-951-682-968-8.

30. Haavisto, I. Tietomallintaminen Korjausrakentamisen Rakennesuunnittelussa (BIM at Structural Engineering in Renovation Projects). Master's Thesis. Tampere University of Technology, Degree programme in Civil Engineering. Tampere, Finland. 2013.

31. Rajala, M. Common BIM Requirements 2012, Series 2: Modeling of the Starting Situation. [Online publication]. 2012. [Referred 19.04.2016]. Available from: http://www.en.buildingsmart.kotisivukone.com/3

32. Helander, D. Assessing Alternatives for using Building Information Models to Manage Initial Information in Building Renovation Projects. Master's Thesis. Aalto University, School of Engineering, Degree programme in Structrual Engineering and Building Technology. Espoo, Finland. 2014.

33. The American Institute of Architects. AIA Document G202TM - 2013: Project Building Information Modeling Protocol Form. [Online document]. 2013. [Referred 27.03.2016]. Available from: http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab099086.pdf

34. BIMForum. Level of Development Specification 2015. [Online document] 2015. [Referred 27.03.2016]. Available from: http://bimforum.org/lod/

35. Autodesk Sustainability Workshop. Project Phases & Level of Development. [Online publication]. [Referred 28.03.2016] Available from: http://sustainabilityworkshop.autodesk.com/buildings/project-phases-level-development

36. McPhee, A. What is this thing called LOD. [Online publication]. Practical BIM, 2013. [Referred 28.03.16]. Available from: http://practicalbim.blogspot.fi/2013/03/what-is-this-thing-called-lod.html

37. Davies, N., Woddy, P. Wenman, L., Purvis, R., Light, D. and Seymour-Smith, C. AEC (UK) BIM Procol: Implementing UK BIM Standards for the Architectural, Engineering and Construction Industry. [Online document]. 2012. [Referred 28.03.2016]. Available from: https://aecuk.files.wordpress.com/2012/09/aecukbimprotocol-v2-0.pdf

38. Gröger, G., Kolbe, T.H. and Czerwinski, A. Candidate OpenGIS® CityGML Implementation Specification (City Geography Markup Language), Version 0.4.0.

[Online document] Open Geospatial Consortium Inc, 2007. [Referred 29.03.2016]. Available from: http://www.opengeospatial.org/docs/is

39. Cong, Z., Cahill, B. and Menzel, K. Analysis of Energy Simulation Models. [Online publication]. University College Cork, Cork, Ireland, 2009. [Referred 02.04.2016]. Available from: http://zuse.ucc.ie/~brian/publications/2009/20090630_Analysis_of_Energy_Simulation_Models_Cong_BC_KMZ.pdf

40. Booth, A. IES VE Introductory Tutorial: Building Energy Simulation. [Online document]. 2010. [Referred 06.04]. Available from: http://www-embp.eng.cam.ac.uk/software/IEStutorial2010.pdf

41. Harish, V.S.K.V. and Kumar, A. A Review on Modeling and Simulation of Building Energy Systems. Renewable and Sustainable Energy Reviews, 2016. Vol. 56. pp. 1272-1292. ISSN 1364-0321.

42. Li, X. and Wen, J. Review of Building Energy Modeling for Control and Operation. Renewable and Sustainable Energy Reviews, 2014. Vol. 37. pp. 517-537. ISSN 1364-0321.

43. Granlund Oy. RIUSKA - Efficient Comfort and Energy Simulation. [Online publication]. [Referred 30.08.2016]. Available from: http://www.granlund.fi/en/software/riuska/

44. Helton, J.C., Johnson, J.D., Sallaberry, C.J. and Storlie, C.B. Survey of Sampling-Based Methods for Uncertainty and Sensitivity Analysis. Reliability Engineering & System Safety, 2006. Vol. 91, no. 10–11. pp. 1175-1209. ISSN 0951-8320.

45. Hopfe, C.J. and Hensen, J.L.M. Uncertainty Analysis in Building Performance Simulation for Design Support. Energy and Buildings, 2011. Vol. 43, no. 10. pp. 2798-2805. ISSN 0378-7788.

46. Silva, A.S. and Ghisi, E. Uncertainty Analysis of User Behaviour and Physical Parameters in Residential Building Performance Simulation. Energy and Buildings, 2014. Vol. 76. pp. 381-391. ISSN 0378-7788.

47. Hopfe, C. J. Uncertainty and Sensitivity Analysis in Building Performance Simulation for Decision Support and Design Optimization. Doctoral thesis. Eindhoven University of Technology. 2009. ISBN 978-90-6814-617-2.

48. Rodríguez G.C., Andrés A. C., Muñoz F.D., López, J.M.C. and Zhang, Yi. Uncertainties and Sensitivity Analysis in Building Energy Simulation using Macroparameters. Energy and Buildings, 2013. Vol. 67. pp. 79-87. ISSN 0378-7788.

49. Helton, J.C., Johnson, J.D., Sallaberry, C.J. and Storlie, C.B. Survey of Sampling-Based Methods for Uncertainty and Sensitivity Analysis. Reliability Engineering & System Safety, 2006. Vol. 91, no. 10–11. pp. 1175-1209. ISSN 0951-8320.

50. De Wit, S. and Augenbroe, G. Analysis of Uncertainty in Building Design Evaluations and its Implications. Energy and Buildings, 2002. Vol. 34, no. 9. pp. 951-958. ISSN 0378-7788.

51. Lam, J.C., Wan, K.K.W. and Yang, L. Sensitivity Analysis and Energy Conservation Measures Implications. Energy Conversion and Management, 2008. Vol. 49, no. 11. pp. 3170-3177. ISSN 0196-8904.

52. Hygh, J.S., Decarolis, J.F., Hill, D.B. and Ranji Ranjithan, S. Multivariate Regression as an Energy Assessment Tool in Early Building Design. Building and Environment, 2012. Vol. 57. pp. 165-175. ISSN 0360-1323.

53. Burhenne, S., Tsvetkova, O., Jacob, D., Henze ,G.P. and Wagner, A. Uncertainty Quantification for Combined Building Performance and Cost-Benefit Analyses. Building and Environment, 2013. Vol. 62. pp. 143-154. ISSN 0360-1323.

54. Massart, D.L., Smeyers-Verbeke, J., Capron, X. and Schlesier, K. Visual Presentation of Data by Means of Box Plots. [Online publication]. LC•GC Europe, 2005. Vol. 18, no. 4. pp. 215-218. [Referred 05.09.2016]. Available from: http://www.csee.umbc.edu/courses/graduate/CMSC601/Spring11/papers/box_charts.pdf

55. Granlund Oy. NewTREND Delivedable 2.1 (Version 0.4): New Approach for an Advanced Data Collection Process, 2016.

56. Intelligent Energy Europe (IEE). IEE Project TABULA (2009 - 2012). [Online publication]. 2012. [Referred 09.08.2016]. Available from: http://episcope.eu/iee-project/tabula

57. Macdonald, I. A. Comparison of Sampling Based Techniques on the Performance of Monte Carlo Based Sensitivity Analysis. [Online publication]. Eleventh International IBPSA Conference, 2009. Glasgow, Scotland. [Referred 06.06.2016]. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.299.1252&rep=rep1&type=pdf

58. City of Seinäjoki. About Seinäjoki. [Online publication]. [Referred 08.06.2016]. Available from: https://www.seinajoki.fi/en/index/cityofseinajoki/aboutseinajoki.html

59. Puska, A. Energiansäästötoimenpiteet Rakennusautomaatiota Hyödyntäen. Aalto University Professional Development - Aalto PRO. Seinjoki, Finland, 2015.

60. Ympäristöministeriö. Ympäristöministeriön asetus rakennuksen energiatodistuksesta, Liite 1: Energiatodistuksen kokonaisenergiankulutuksen (E-Luvun) määrittäminen. [Online document]. 2013. [Referred 06.06.2016]. Available from: http://www.finlex.fi/data/sdliite/liite/6186.pdf

61. Vuolle, M. and Airaksinen, M. Energiatodistusopas, Liite: Tyypillisiä olemassa olevien vanhojen rakennusten alkuperäisiä suunnitteluarvoja. [Online document]. Ympäristöministeriö, 2013. [Referred 06.06.2016]. Available from: http://www.ymparisto.fi/fi-FI/Rakentaminen/Rakennuksen_energia_ja_ekotehokkuus/Rakennuksen_energiatodistus/Energiatodistuslomakkeet

62. Ympäristöministeriö. Suomen Rakentamismääräyskokoelma D5: Rakennusten energiankulutuksen ja lämmitystehontarpeen laskenta. [Online document]. 2013. [Referred 15.05.16]. Available from: http://www.ym.fi/Rakentamismaarayskokoelma

63. Ympäristöministeriö. Tasauslaskentaopas 2012: Rakennuksen lämpöhäviön määräystenmukaisuuden osoittaminen. [Online document]. 2011. [Referred 12.06.2016]. Available from: http://www.ym.fi/Rakentamismaarayskokoelma

64. Motiva. Laskukaavat: lämmin käyttövesi. [Online publication]. [Referred 13.06.2016] Available from: http://www.motiva.fi/julkinen_sektori/energiankayton_tehostaminen/kiinteistojen_energianhallinta/kulutuksen_normitus/laskukaavat_lammin_kayttovesi

65. Ympäristöministeriö. Suomen Rakentamismääräyskokoelma D2: Rakennusten sisäilmasto ja ilmanvaihto. [Online document]. 2011. [Referred 25.06.2016] Available from: http://www.finlex.fi/data/normit/37187-D2-2012_Suomi.pdf

66. Jylhä, K., Kalamees, T., Tietäväinen, H., Ruosteenoja, K., Jokisalo, J., Hyvönen, R., Ilomets, S., Saku, S., and Hutila, A. Rakennusten energialaskennan testivuosi 2012 ja arviot ilmastonmuutoksen vaikutuksista. Finnish Meteorological Institute, 2011. ISBN 978-951-697-756-3.

67. Sirén, K. Rakennusten Energiainvestointien Kannattavuuden Laskenta. [Course material]. Aalto University.

68. Holopainen, R., Vares, S., Ritola, J. and Pulakka, S. Maalämmön ja -viilennyksen hyödyntäminen asuinkerrostalon lämmityksessä ja jäähdytyksessä. Technical Research Center of Finland, 2010. ISBN 978-951-38-7644-9.

Appendixes

Appendix 1. Investment cost data and economic variables used in the LCC calculations
Appendix 2. Building usage schedules used in the advanced mode
Appendix 3. Air flows, HRU efficiencies and investment costs of the retrofitted ventilation system types

Appendix 1. Investment cost data and economic variables used in the LCC calculations

Insulation costs of wall and roof with ISOVER KL-33 mineral wool			
Thicness	Mat. (€/m2) 1)	Work (€/m2) 2)	Total (€/m2)
50	4,4	3,8	8,2
100	6,85	3,8	10,65
150	10,3	3,8	14,1
200	13,95	3,8	17,75
400	27,9	7,6	35,5

Sources:
1) *ISOVER price list (available: http://saint-gobain.digtator.fi/Default.aspx#!prettyPhoto)*
2) *Granlund's internal documents. Demolition of old wall not included, actual costs would be higher.*

Window renewal costs in € for a 2,5 m^2 window.						
Demolition	New window (1,00 W/m^{2}K)	New window (0,80 W/m^{2}K)	Installation	Connection with wall	Window sill	Jamb moulding
100	320	432	55	82	26	92

Source: Granlund's internal documents.

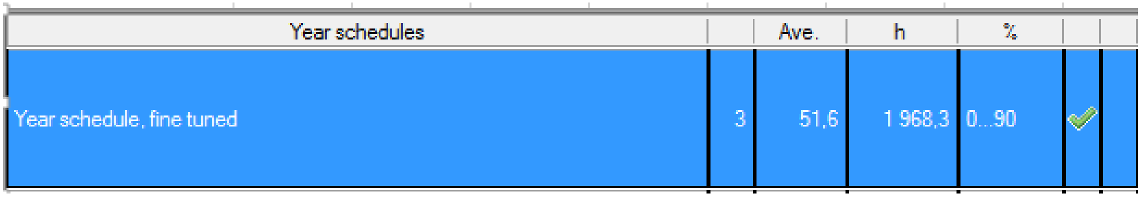
Used economic variables	
Electricity price [€/kWh]	0,10
District heat price [€/kWh]	0,06254
Interest rate	3 %
Calculation time	25 years

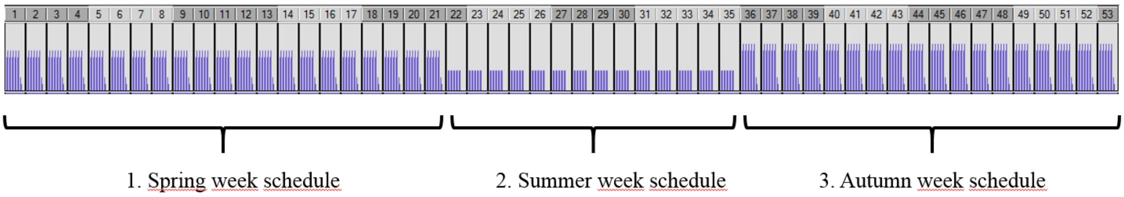
Source for prices: Local energy company website: www.seinäjoenenergia.fi
Prices include transmission costs and taxes

Appendix 2. Building usage schedules used in the advanced mode

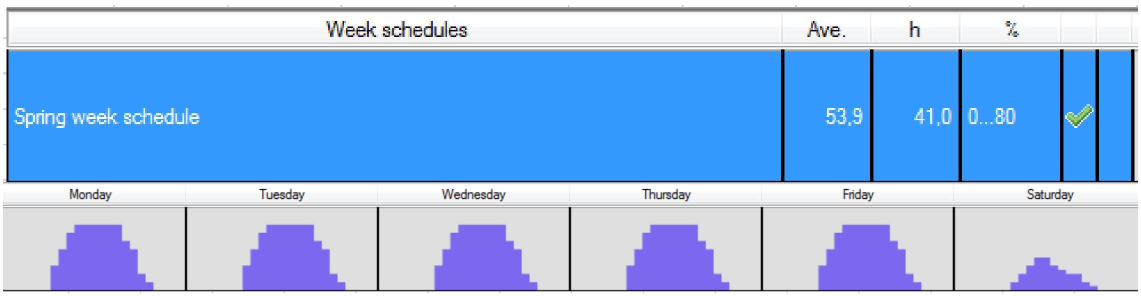
These schedules were used for all internal loads (lighting, equipment and people) in the advanced mode simulations. They were created based on known opening hours of the building, and fine-tuned to match the monthly measured electricity consumptions. The schedules are described here with figures taken from the RIUSKA software. In RIUSKA, year schedules consists of week schedules, and week schedules consist of day schedules. In this work, the yearly schedule was divided into three parts (spring, summer and autumn), which have slightly different weekly schedules. In the figures below "*Ave*" means the average utilization rate, "*h*" means the hours multiplied with the utilization rate and "*%*" tells the range of utilization rates used in the schedule. The building is assumed to be closed every Sunday, and thus Sundays are not shown here. In the summer season, it is also assumed that the building is not at all in use in Saturdays.

Year Schedule

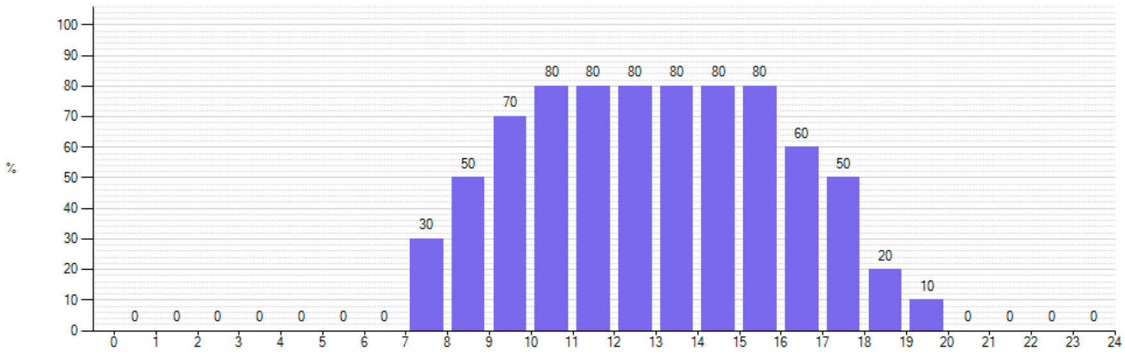




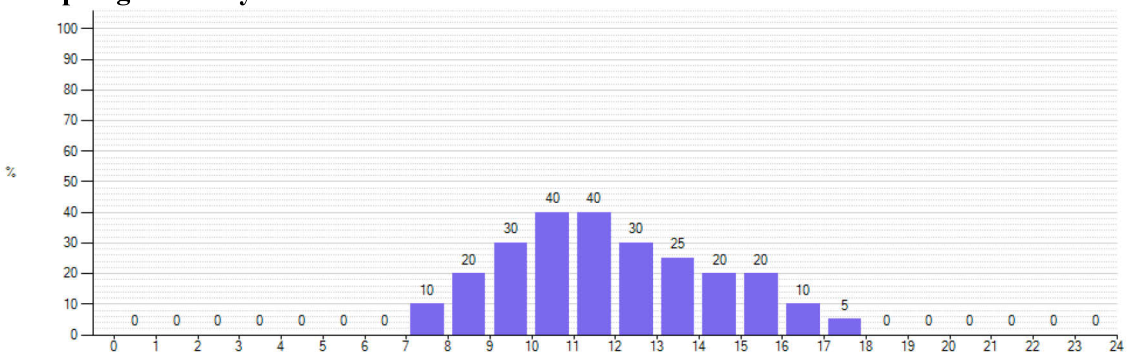
1. Spring week schedule (January – May, weeks 1 – 21)



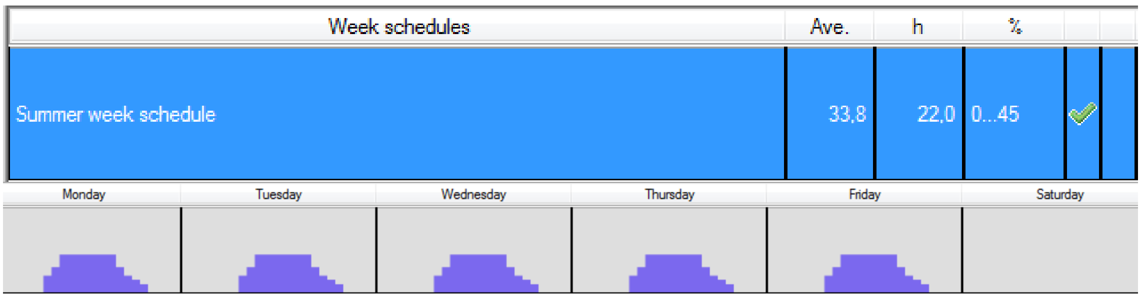
1.1 Spring weekday schedule



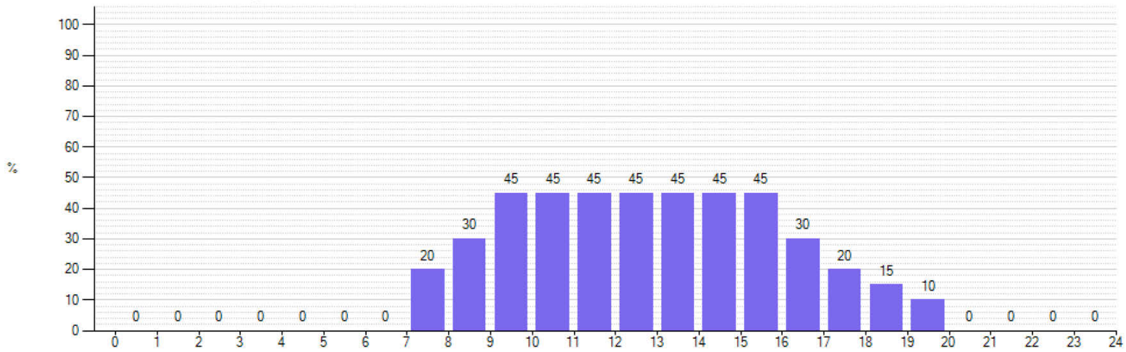
1.2 Spring Saturday schedule



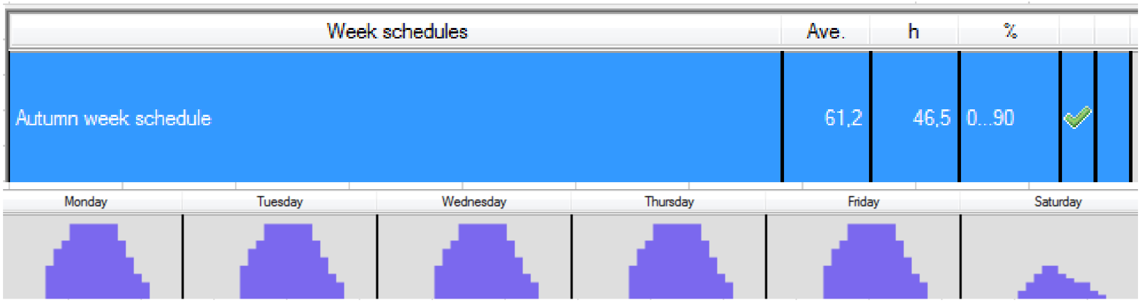
2. Summer week schedule (June – August, weeks 22 – 35)



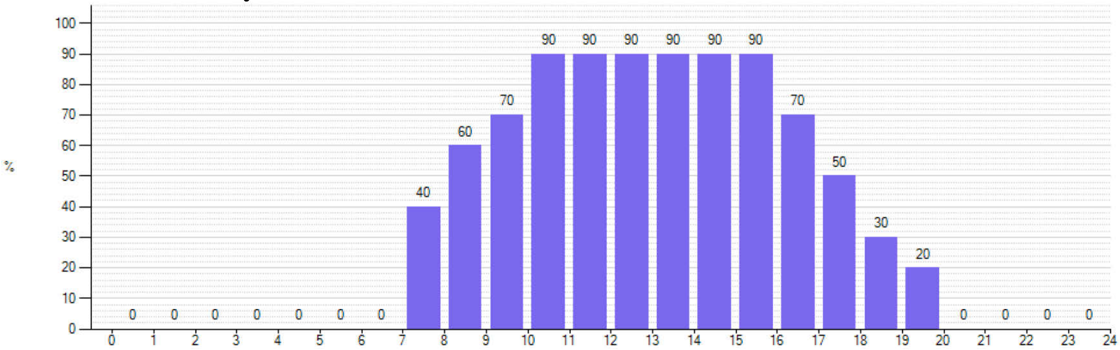
2.1 Summer weekday schedule



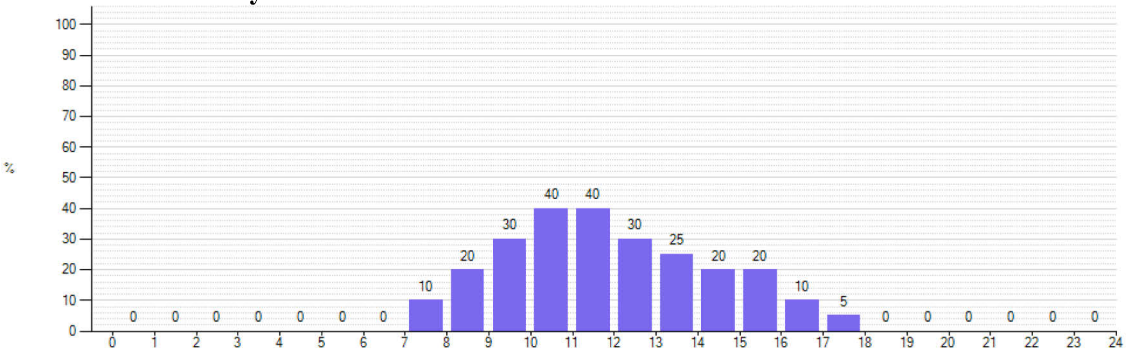
3. Autumn week schedule (September – December, weeks 36 – 53)



3.1 Autumn weekday schedule



3.2 Autumn Saturday schedule



Appendix 3. Air flows, HRU efficiencies and investment costs of the retrofitted ventilation system types

Table 1. Air flows and HRU efficiencies of the retrofitted ventilation system types.

Type	Description	Maximum air flows [m3/s] [1]			HRU efficiency [2]		
		TK/PK1	TK/PK2.1	TK/PK2.2	TK/PK1	TK/PK2.1	TK/PK2.2
1	CAV system	7,79	9,04	3,07	79 %	77 %	62 %
2	CAV system with cooling of supply air	7,79	9,04	3,07			
3	DCV system	7,79	9,04	3,07			
4	DCV system with cooling of supply air	8,17	9,10	3,07			

Sources:
1) Air flow rates for cases 1 - 3 were determined to satisfy the Finnish building regulations part D3. Air flow rates for case 4 were sized with RIUSKA, so that the temperature in DCV rooms do not exceed 25 °C in design day conditions.
2) The AHU models were chosen with the dimensioning and LCC software "Future++" from Koja, from which also the HRU efficiencies were obtained.

Table 2. Investment costs of the retrofitted ventilation system types.

Type	Description	TK/PK1 [1]	TK/PK2.1 [1]	TK/PK2.2 [1]	Cooling (150kW) [2]	Occupancy sensors [3]	Total
1	CAV system	52 000 €	53 000 €	27 000 €	0 €	0 €	132 000 €
2	CAV system with cooling of supply air	60 000 €	61 000 €	31 000 €	47 000 €	0 €	199 000 €
3	DCV system	52 000 €	53 000 €	27 000 €	0 €	200 000 €	332 000 €
4	DCV system with cooling of supply air	61 000 €	62 000 €	31 000 €	47 000 €	200 000 €	401 000 €

Sources:
1) Investment costs of AHUs were obtained from the dimensioning and LCC software "Future++" from Koja (http://www.koja.fi/fi/rakennukset/ratkaisut/future-mitoitusohjelma).
2) The maximum cooling demand of the building (150kW) was sized with RIUSKA, and the investment cost of the cooling system was estimated based on a catalog of Onninen (http://www.onninen.com/finland/Palvelut/Hinnastot/Pages/Kylmatuotteet.aspx).
3) The investment costs of the occupancy sensors required by the DCV system were estimated based on Granlund's internal documents. The average investment cost per treated floor area was calculated from the cost estimates of precious projects, which was then used to roughly estimate the investment costs for this building.